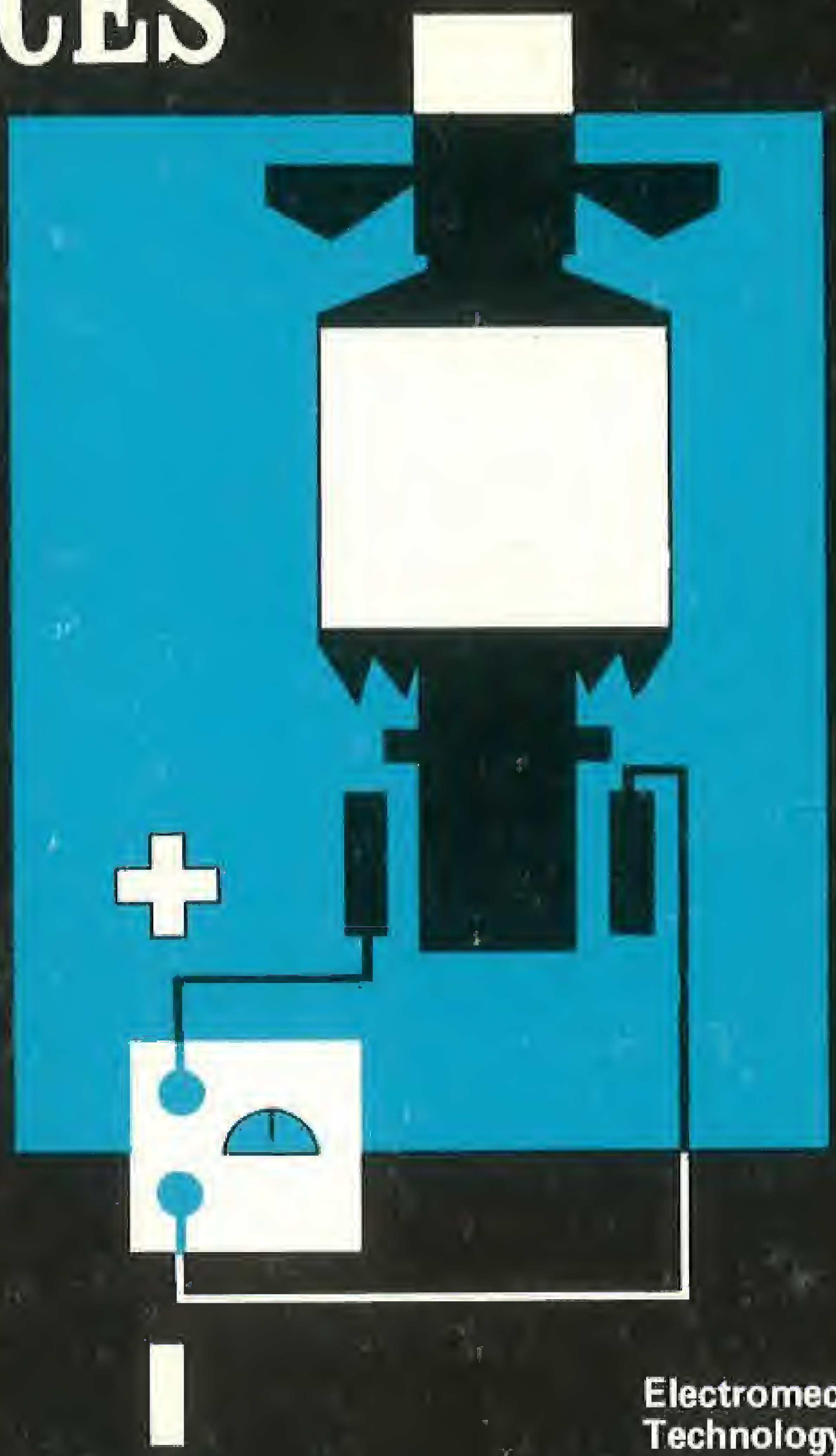
TERC

ELECTRO MECHANISMS

DEVICES



Electromechanical Technology Series

TERC EMT STAFF

DELMAR PUBLISHERS, MOUNTAINVIEW AVENUE, ALBANY, NEW YORK 12205

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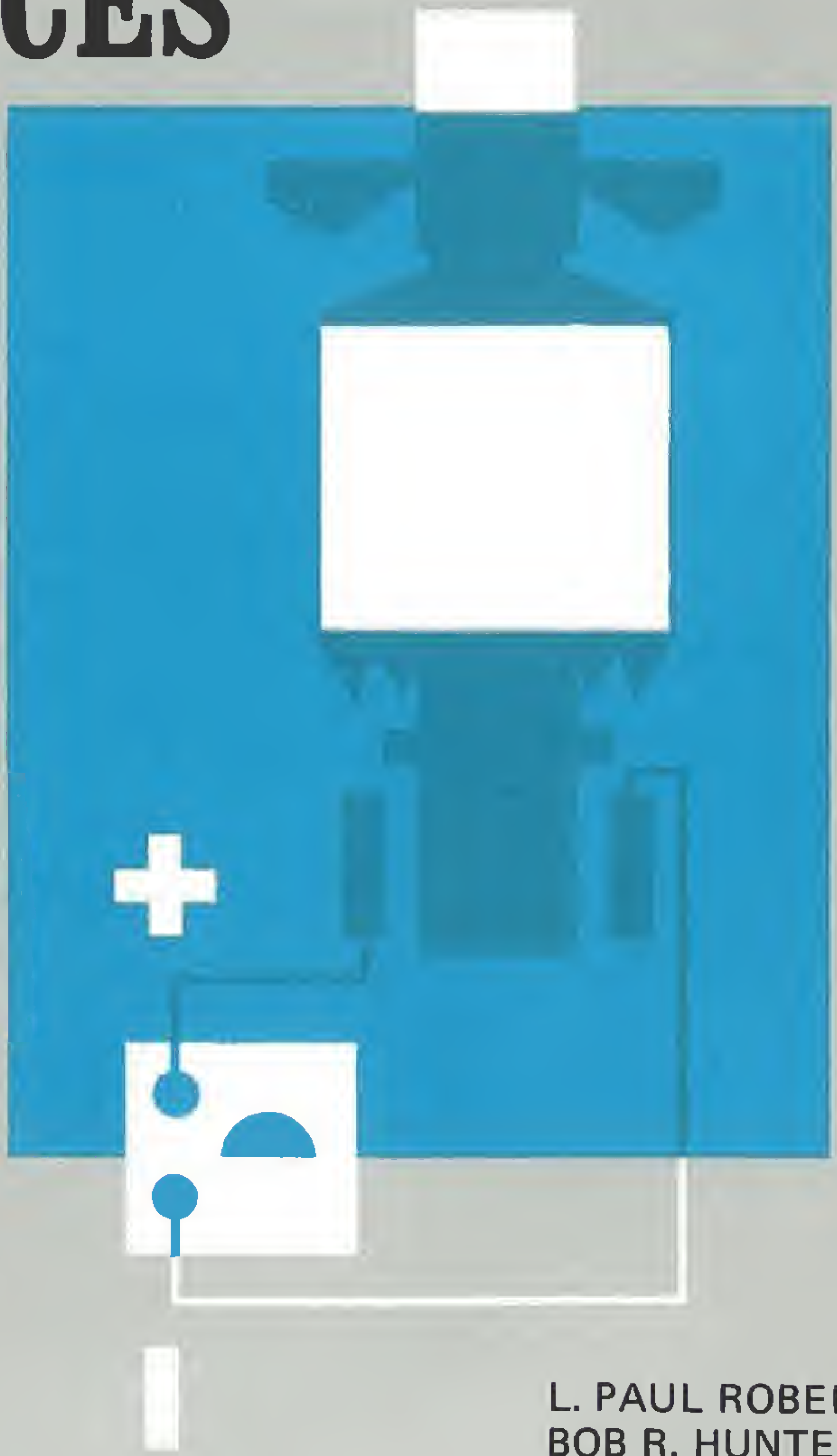

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Foreword

The marriage of electronics and technology is creating new demands for technical personnel in today's industries. New occupations have emerged with combination skill requirements well beyond the capability of many technical specialists. Increasingly, technicians who work with systems and devices of many kinds — mechanical, hydraulic, pneumatic, thermal, and optical — must be competent also in electronics. This need for combination skills is especially significant for the youngster who is preparing for a career in industrial technology.

This manual is one of a series of closely related publications designed for students who want the broadest possible introduction to technical occupations. The most effective use of these manuals is as combination textbook-laboratory guides for a full-time, post-secondary school study program that provides parallel and concurrent courses in electronics, mechanics, physics, mathematics, technical writing, and electromechanical applications.

A unique feature of the manuals in this series is the close correlation of technical laboratory study with mathematics and physics concepts. Each topic is studied by use of practical examples using modern industrial applications. The reinforcement obtained from multiple applications of the concepts has been shown to be extremely effective, especially for students with widely diverse educational backgrounds. Experience has shown that typical junior college or technical school students can make satisfactory progress in a well-coordinated program using these manuals as the primary instructional material.

School administrators will be interested in the potential of these manuals to support a common first-year core of studies for two-year programs in such fields as: instrumentation, automation, mechanical design, or quality assurance. This form of *technical core* program has the advantage of reducing instructional costs without the corresponding decrease in holding power so frequently found in general core programs.

This manual, along with the others in the series, is the result of six years of research and development by the *Technical Education Research Center, Inc.,* (TERC), a national nonprofit, public service corporation with headquarters in Cambridge, Massachusetts. It has undergone a number of revisions as a direct result of experience gained with students in technical schools and community colleges throughout the country.

Maurice W. Roney

The Electromechanical Series

TERC is engaged in an on-going educational program in *Electromechanical Technology.* The following titles have been developed for this program:

INTRODUCTORY

ELECTROMECHANISMS/MOTOR CONTROLS
ELECTROMECHANISMS/DEVICES
ELECTRONICS/AMPLIFIERS
ELECTRONICS/ELECTRICITY
MECHANISMS/DRIVES
MECHANISMS/LINKAGES
UNIFIED PHYSICS/FLUIDS
UNIFIED PHYSICS/OPTICS

ADVANCED

ELECTROMECHANISMS/AUTOMATIC CONTROLS
ELECTROMECHANISMS/SERVOMECHANISMS
ELECTROMECHANISMS/FABRICATION
ELECTROMECHANISMS/TRANSDUCERS
ELECTRONICS/COMMUNICATIONS
ELECTRONICS/DIGITAL
MECHANISMS/MACHINES
MECHANISMS/MATERIALS

For further information regarding the EMT program or for assistance in its implementation, contact:

Technical Education Research Center, Inc.
44A Brattle Street
Cambridge, Massachusetts 02138

Preface

Electromechanical systems as a whole form a large part of all our technologies. They range from simple everyday things like lamp switches to extremely complicated systems in computers or space vehicles.

The study of these devices and systems constitutes much of what might be called practical science. This study should start with the simpler devices and proceed to the more complex. In this way the field develops as an orderly sequence of understanding. Any other approach can result in unnecessary confusion on the part of the learner.

Electromechanisms/Devices attempts to present such devices as motors, generators, relays, solenoids and other selected topics in a simple and direct manner.

The sequence of presentation chosen is by no means inflexible. It is expected that individual instructors may choose to use the materials in other than the given sequence.

The particular topics chosen for inclusion in this volume were selected primarily for convenience and economy of materials. Some instructors may wish to omit some of the exercises or to supplement some of them to better meet their local needs.

The materials are presented in an action-oriented format combining many of the features normally found in a textbook with those usually associated with a laboratory manual. Each experiment contains:

1. An INTRODUCTION which identifies the topic to be examined and often includes a rational for doing the exercise.
2. A DISCUSSION which presents the background, theory, or techniques needed to carry out the exercise.
3. A MATERIALS list which identifies all of the items needed in the laboratory experiment. (Items usually supplied by the student such as pencil and paper are not included in the lists.)
4. A PROCEDURE which presents step-by-step instructions for performing the experiment. In most instances the measurements are done before calculations so that all of the students can at least finish making the measurements before the laboratory period ends.
5. An ANALYSIS GUIDE which offers suggestions as to how the student might approach interpretation of the data in order to draw conclusions from it.
6. PROBLEMS are included for the purpose of reviewing and reinforcing the points covered in the exercise. The problems may be of the numerical solution type or simple questions about the exercise.

Students should be encouraged to study the textual material, perform the experiment, work the review problems, and submit a technical report on each topic. Following this pattern, the student can acquire an understanding of, and skill with, electromechanical devices that will be very valuable on the job. For best results, these students should be concurrently enrolled in a course in technical mathematics (algebra and trigonometry).

These materials comprise one of a series of volumes prepared for technical students by the TERC EMT staff at Oklahoma State University, under the direction of D. S. Phillips and R.W. Tinnell. The principal authors of these materials were L. Paul Robertson, Bob R. Hunter, and Richard L. Allan.

An *Instructor's Data Book* is available for use with this volume. Mr. Richard Allan was responsible for testing the materials and compiling the instructor's data book for them. Other members of the TERC staff made valuable contributions in the form of criticisms, corrections and suggestions.

It is sincerely hoped that this volume as well as the other volumes in the series, the instructor's data books, and other supplementary materials will make the study of technology interesting and rewarding for both students and teachers.

THE TERC EMT STAFF

TO THE STUDENT

Duplicate data sheets for each experiment are provided in the back of the book. These are perforated to be removed and completed while performing each experiment. They may then be submitted with the experiment analysis for your instructor's examination.

Contents

experiment 1 SOURCES OF INFORMATION

INTRODUCTION. The purpose of this exercise is to acquaint you with the various types and classes of literature in the electromechanical field and with sources regarding components and systems.

DISCUSSION. Steinmetz said, "There are no foolish questions — and no man becomes a fool until he has stopped asking questions." Only by knowing more can we make intelligent choices and find out how to do the things we want to do. No human being has the mental capacity to know everything he needs to know, but he can find out almost anything he wants to know.

In our library there are large numbers of books, periodicals, reports, and other publications telling about the methods that scientists, engineers and technicians use in their work. This information describes the experimental systems, the testing techniques, the theoretical background, reports of newly developed components and techniques, and similar items of interest to the electromechanical technician.

As you grow in technical knowledge, it is important that you be aware of the accomplishments in your field. In your formal education you will be exposed to only a very small amount of the available knowledge, and knowledge does not stop being created after you are out of school. In order for you to grow, and for that matter, for you to keep up, you must be aware of the literature in the field of electromechanical technology.

Technical literature is generated primarily by four groups: (1) governmental agencies; (2) non-profit corporations and foundations; (3) educational institutions; and (4) industrial organizations. Naturally, private individuals write books, handbooks, and articles and have these published in journals and by book publishers. Much of the literature produced never finds its way into libraries and is often difficult to obtain. This is especially true of some governmental reports and of privately sponsored information created in industry. The literature that does receive distribution can be found in several types of publications. Some of these types are:

1. **Office of Technical Services of the U.S. Department of Commerce publications.**
2. **Government publications by various agencies.**
3. **Technical magazines and trade journals.**
4. **Papers, journals, etc. of engineering societies.**
5. **Master and doctoral theses.**
6. **Books.**

If you are looking for a particular bit of information, how do you start? One excellent way is to begin with an Index of some sort. An Index results from people searching through the literature and listing what they have found. There are many different types of Indices and some of the ones used by electromechanical technicians when searching for information are: U. S. Government Research Reports, Nuclear Science Abstracts, Applied Science and Technology Index, Engineering Index, and many others.

These Indices are arranged in various ways. Some list by the author, some by the subject, and others by the source (such as by Atomic Energy Commission).

Books and periodicals are an important source of information as you already know. Many libraries today use the Library of Congress indexing system. Others use the Dewey Decimal System which classifies information into ten major classes, each of which is subdivided into ten subgroups. Much information relating to electromechanical subjects is found in the 500 class (Pure Science) and in the 600 class (Useful Arts). Each book in the library will have its own separate call number.

How do you find the call number of a book? The library has a *card file* where books are listed three different ways — by subject, by title, and by author. So, when looking for information that may be contained in a book, you go to the card file and search through the files until you locate one that possibly has your information in it. By writing down the call number, the book can be located. A quick check through the table of contents or through the index will quickly tell you if the desired information is in the book.

No matter what you do or where you work after you are out of school, you are paid to do certain tasks. You can often save yourself and your company much time and money by being able to quickly locate information needed in your job. There is nothing more discouraging than to spend hours developing something and then to find out that it has been done many years before.

MATERIALS

Paper and Pen.

PROCEDURE

For each of the following, list the items below:

Call Number: *For all books and, where applicable, for others.*

Author: *For all books.*

Title: *Complete title.*

Source: *Publishing company for books and periodicals.*

Date: *Copyright date of book or publication date of others.*

Coverage: *Not over two sentences describing contents.*

1. A book on automobile solid-state ignition systems.
2. A book on automobile automatic transmissions.
3. An article from *Popular Electronics* on stereo hi-fi systems.
4. An article from *Popular Mechanics* on the road testing of a new anti-pollution fuel.

5. HANDBOOK OF CHEMISTRY AND PHYSICS
6. A book of mathematical tables
7. A Machinist's Handbook
8. Three trade journals (periodicals specializing in electronics/mechanics)
9. An article on new discoveries in magnetism.
10. Assume you wish to purchase some small relays. List the names of three manufacturers that you would recommend to your purchasing department. Where did you find these?
11. You have a broken vacuum valve manufactured by Ultek. Whom would you call to discuss purchasing another? Where did you find his name and telephone number?

ANALYSIS GUIDE. In a short paragraph explain why practically all industrial concerns have a rather large technical library.

PROBLEMS

1. Tell what each of the following terms means:
   (a) Index
   (b) Card file
   (c) Call number
   (d) Periodicals
2. What is the Dewey Decimal System?
3. What kind of subjects are found in the 600 class in a library?
4. What is a trade journal?
5. How many major classes of information would you expect to find in a library?

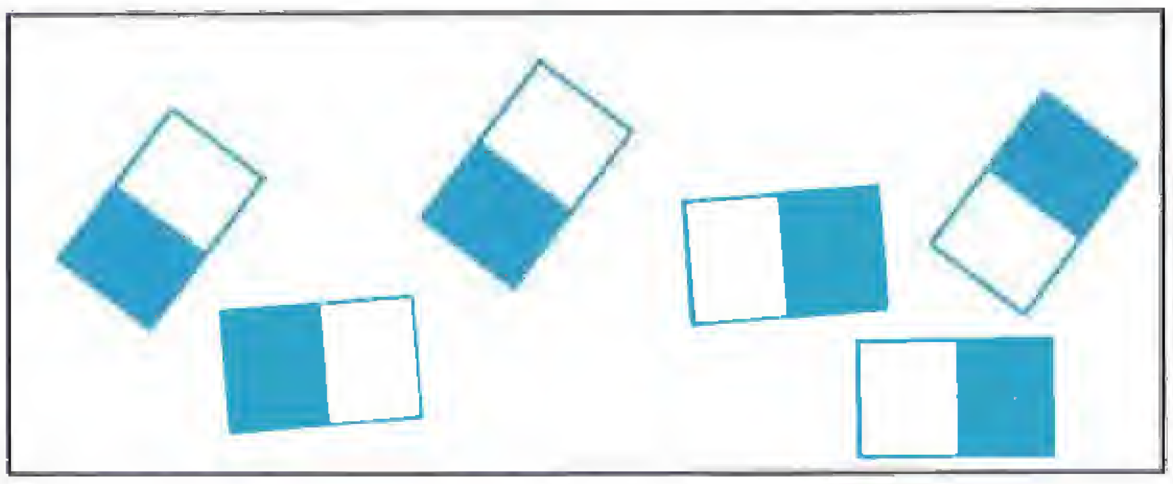
experiment 2 MAGNETIC FIELDS

INTRODUCTION. Magnetism plays a very important role in electromechanical systems. In this experiment we will examine some of the characteristics of *magnets* as they exert *differential forces* on an object.

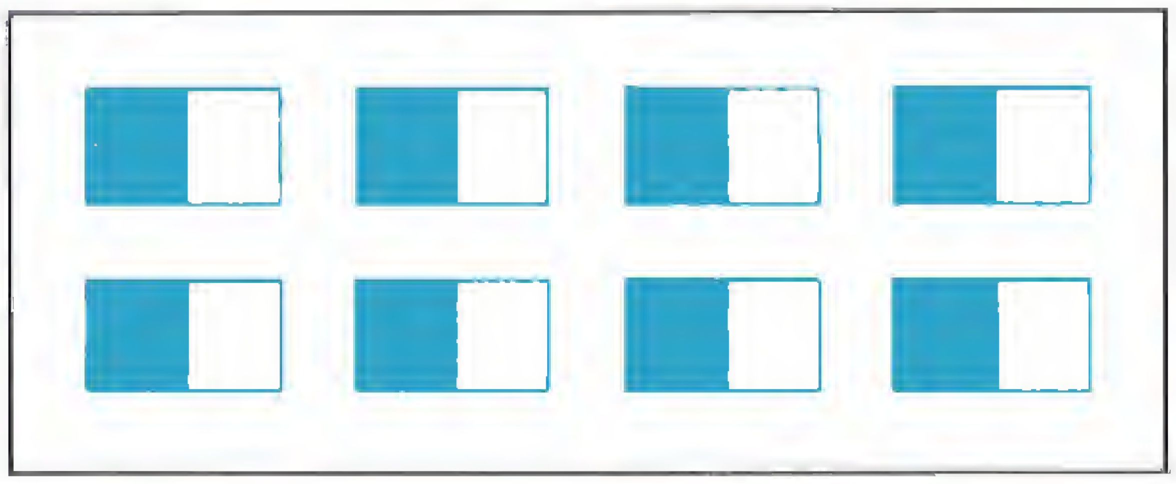
DISCUSSION. Magnets have a wide application in the field of electromechanical technology. They are encountered in such simple devices as door latches or more complicated equipment such as telephones, radios, televisions, temperature controls, and automobiles.

The original permanent magnets, known as *loadstones,* meaning "way stone", were used in mariners' compasses. The name magnet was given to the loadstone because large deposits of the stone were found near the city of Magnesia in Asia Minor. The material of the loadstone is a variety of iron which is found in its natural state in a magnetized condition. This material has been in use since around 155 A.D.

Although it is not known what *magnetism* is, there are several theories that permit us to use magnetism. One theory is that the orbital electrons within a material spin, and this spinning causes each electron to act as an extremely small magnet with a north and south pole. Some materials have about as many electrons spinning in one direction as the other. Therefore, they have practically no resultant magnetism. Other materials, such as iron and cobalt, have more electrons aligned in one direction than other metals and are easier to magnetize. In *ferromagnetic* materials, adjacent atoms will align themselves in the same direction. Groups of these aligned atoms, known as *domains,* are represented in figure 2-1. These domains have force fields that extend their influence into the region immediately surrounding them. This region is called a *magnetic field.* Magnetic materials placed in these fields are acted on by an invisible force that is produced by the field. This force will tend to move the material in a definite direction.



(A) UNMAGNETIZED—RANDOM ALIGNMENT OF DOMAIN



(B) MAGNETIZED— ALIGNED DOMAINS

Fig. 2-1 Molecular Structure of Magnetism.

To study the direction and intensity of a magnetic field, a compass, iron filings and an artificial magnet may be utilized. The artificial magnet is made from a bar of hardened steel. The bar steel is magnetized by inserting it into a magnetic field of sufficient intensity to cause the magnetic domains within the steel to become aligned. Since steel has a high *retentivity* (the ability of a material to retain its magnetism), it is used in the production of permanent magnets.

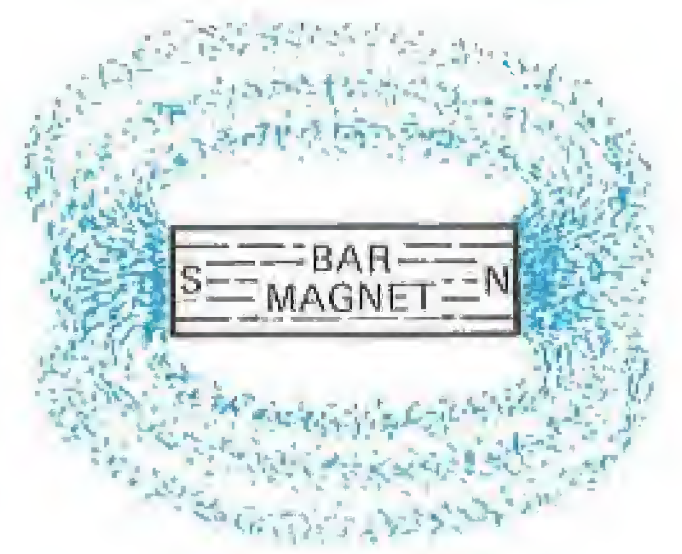


Fig. 2-2 Lines of Force

If iron filings are sprinkled over a bar magnet as shown in figure 2-2, most of the filings will accumulate at the ends of the magnet. These areas at the ends are called the *poles* of the magnet. The filings are most dense at the poles because the magnetic field is more intense where the lines of force are the closest together.

If a bar magnet is suspended by a string, as shown in figure 2-3, so it can turn freely, it will come to rest with one end, termed the *north-seeking pole*, pointing toward the geographical north pole. The other end, termed the *south-seeking pole*, will point toward the geographical south pole.

The force of attraction (f) of unlike poles and/or the force of repulsion (f) of like poles depends on the strength of the poles (m) and the distance (d) between them. The strength of the pole of a magnet is measured in *unit poles*. A unit magnetic pole is one which, if placed in air one centimeter from a similar pole of the same strength, will repel it with a force of one *dyne*. The force of attraction and/or repulsion in dynes upon each pole varies inversely as the square of the distance in centimeters between them. This relationship can be expressed by Coulomb's Law:

$$\boxed{f = \frac{m_1 m_2}{d^2} \text{ dynes}} \qquad (2.1)$$

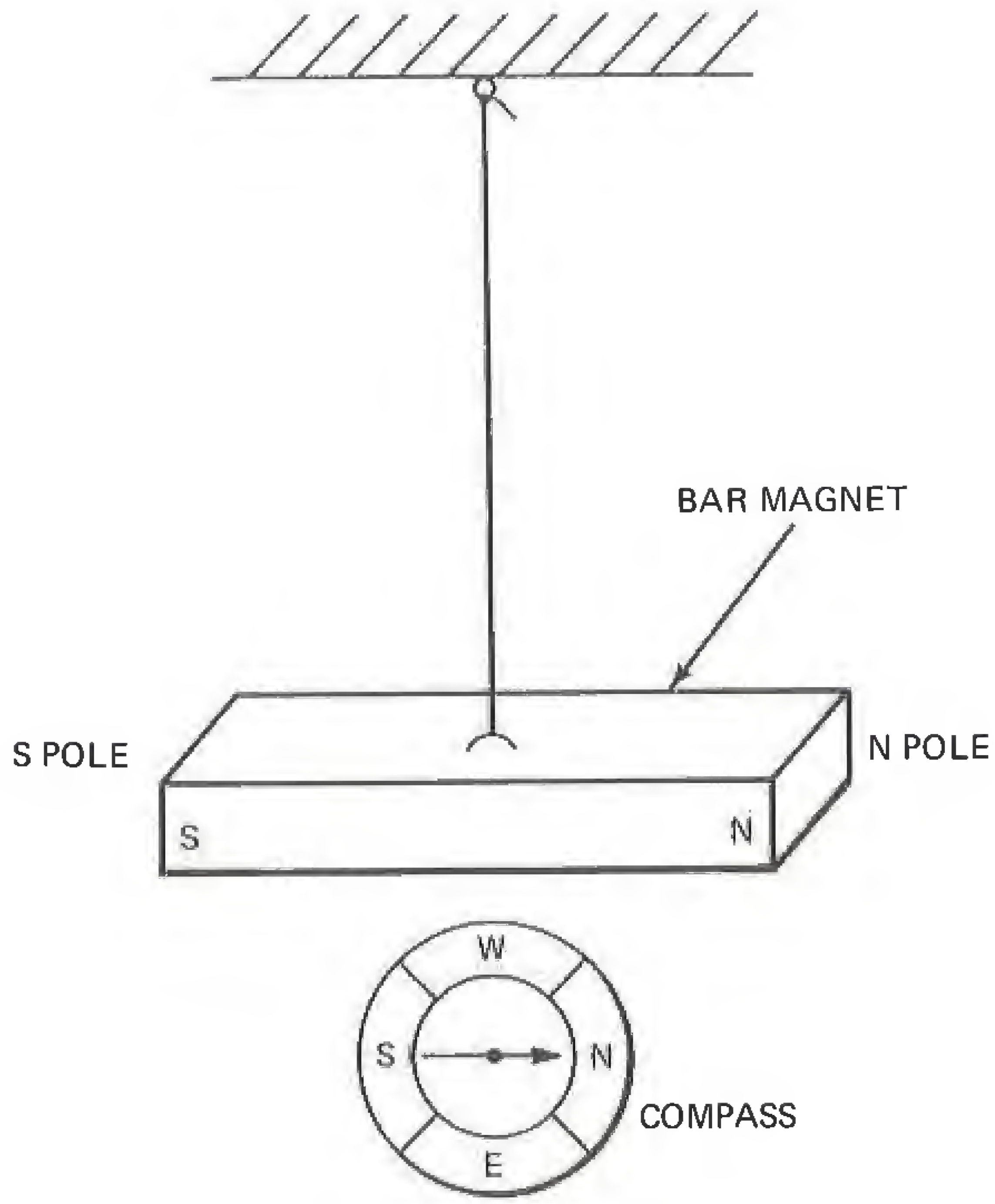


Fig. 2-3 Polarity of a Magnet

If two magnets are brought close to each other, what happens? If the two like poles are close together, the poles repel each other; and if the two unlike poles are brought together, the poles attract each other. This action is shown in figure 2-4.

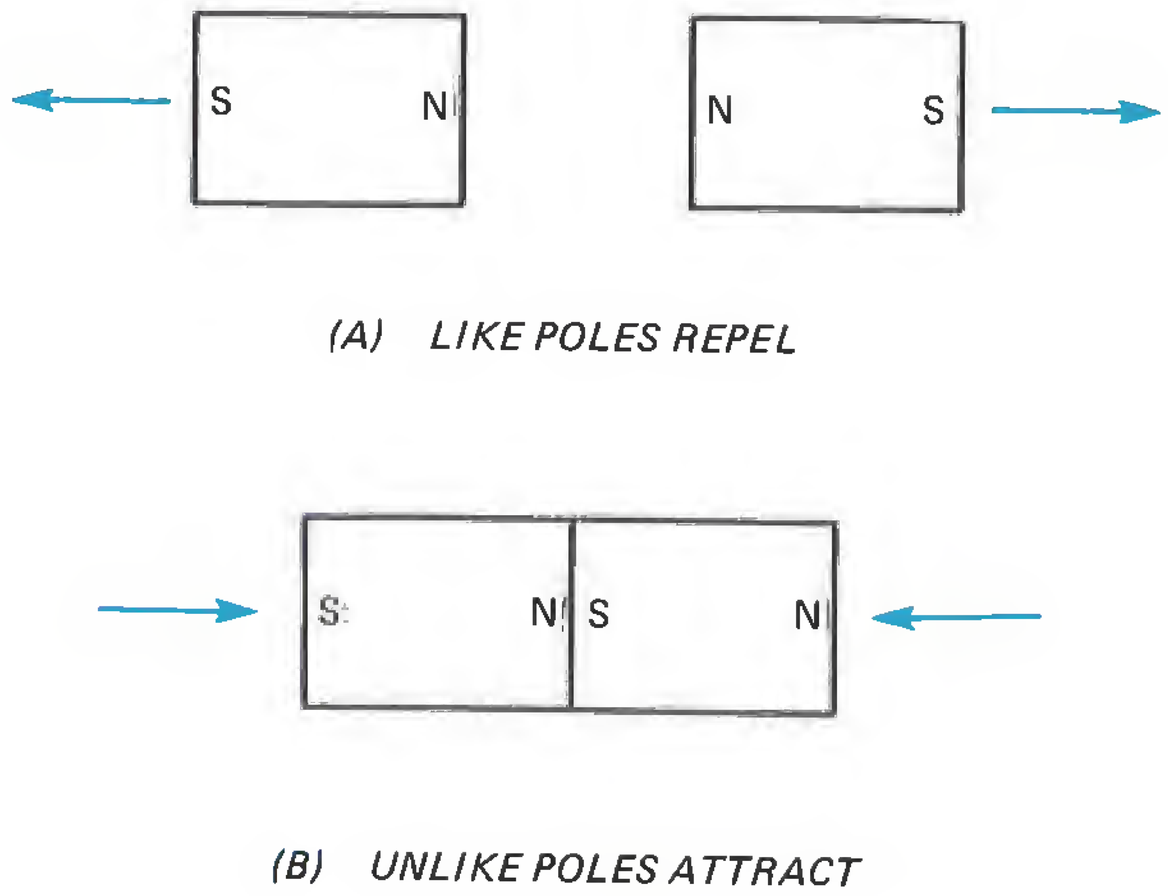


Fig. 2-4 The Reaction of Magnetic Poles to Each Other

EXAMPLE:

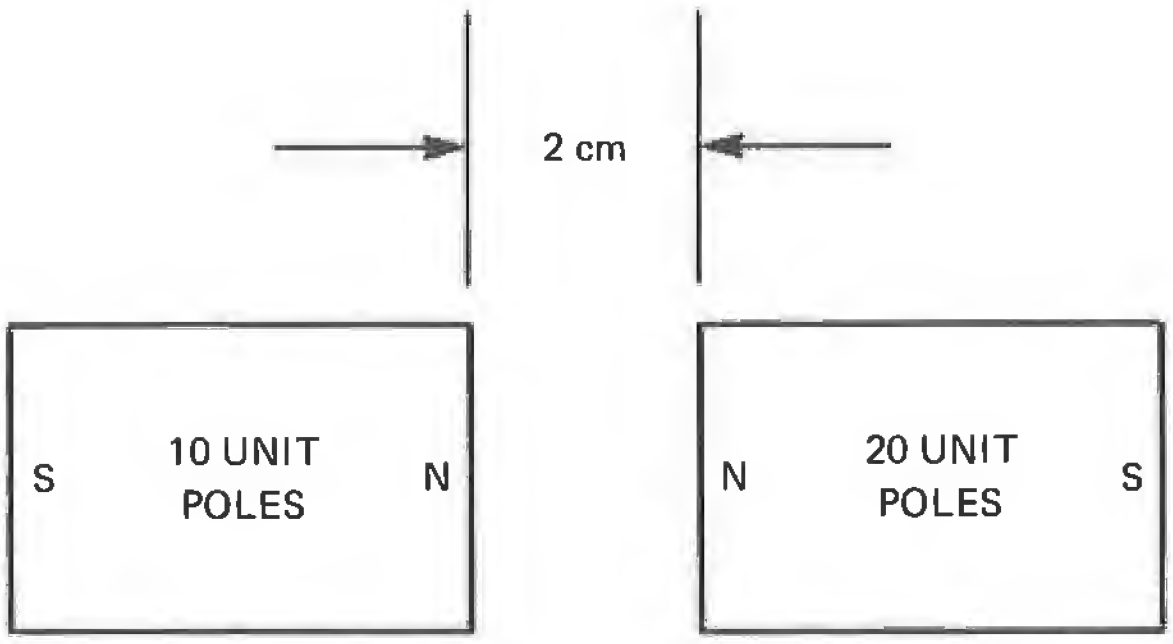
A north pole with a strength of 10 unit poles is placed 2 cm from a north pole whose strength is 20 unit poles. What is the force acting upon each pole?

Given: m_1 = 10 unit poles

m_2 = 20 unit poles

d = 2 cm

Find: f



SOLUTION: $f = \dfrac{m_1\, m_2}{d^2}$

$$f = \frac{(10)\ (20)}{2^2} = \frac{200}{4}$$

f = 50 dynes (repelling)

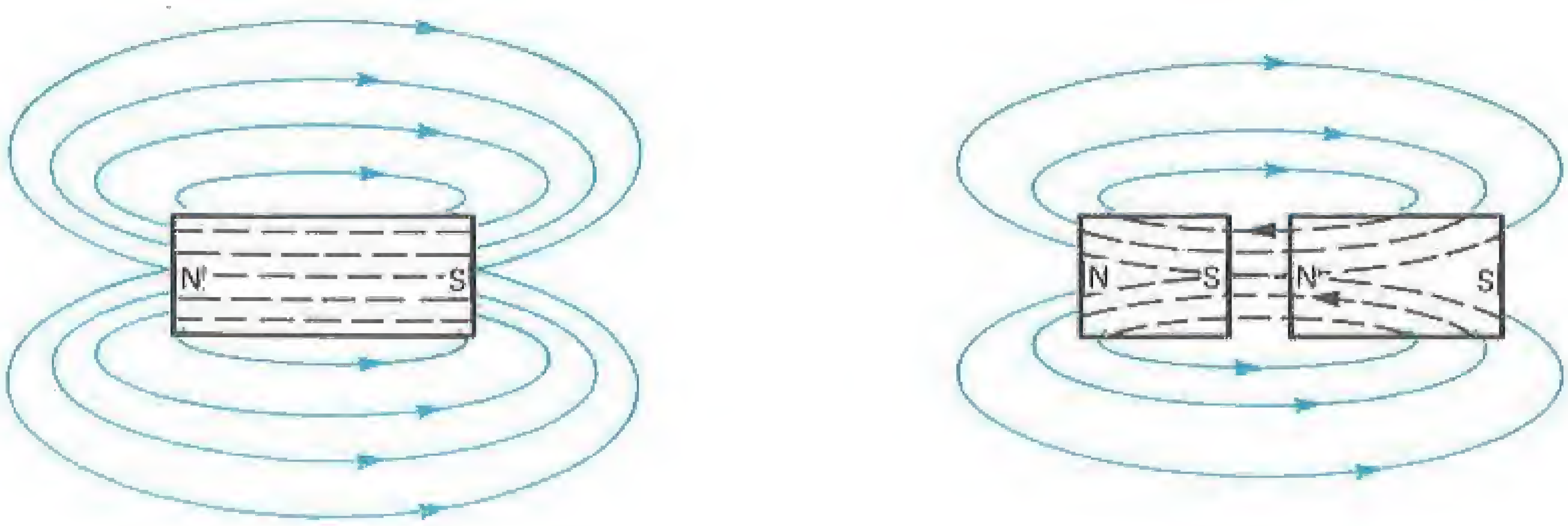
If we bring a bar magnet close to a compass needle, we will find that the compass will be deflected so that one end of the needle always points to one end of the bar magnet. As we move the bar magnet, the compass needle will follow this action. Since the magnet itself does not come into contact with the compass needle, there must be some force associated with the bar magnet responsible for the deflection of the compass needle. This space around the magnet in which the force can be detected is called a *magnetic field.*

If we investigate the magnetic fields of various shapes of magnets with a compass and iron filings, we shall discover several important characteristics of *magnetic lines of force*. The characteristics that the *flux lines* are usually assumed to exhibit are:

1. **Magnetic lines of force possess direction.** Magnetic lines of force always leave the north pole of a magnet and enter the south pole, figure 2-5a.

2. **Magnetic lines of force always form complete loops,** figure 2-5a.

3. **Magnetic lines of force represent a tension along their length which tends to make them as short as possible,** figure 2-5b.



(A) COMPLETE LOOPS & DIRECTION *(B) A TENSION*

Fig. 2-5 Magnetic Lines of Force

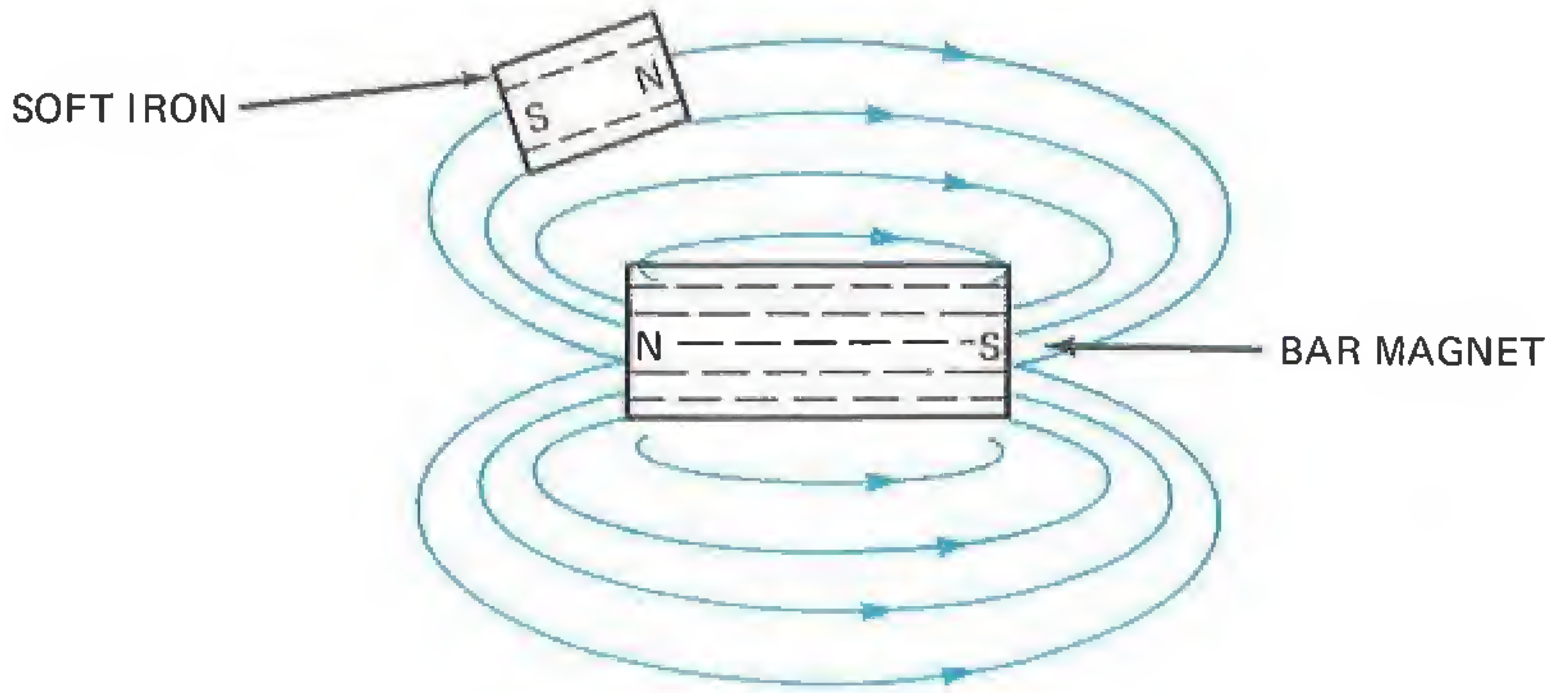


Fig. 2-6 Magnetic Line of Force Tending to Take The Path of Least Opposition

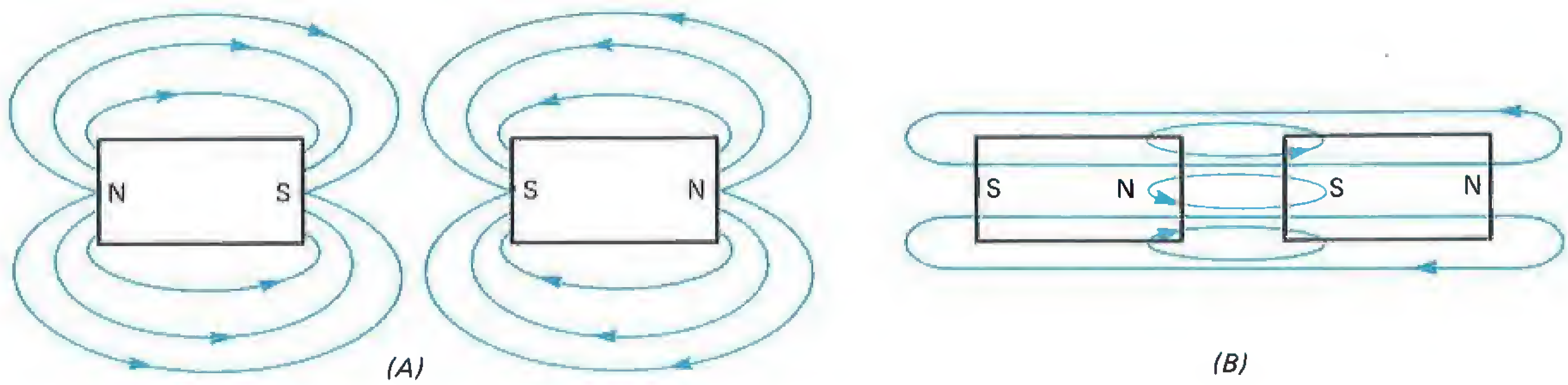


Fig. 2-7 Magnetic Lines of Force

4. **Magnetic lines of force cannot intersect.**

5. **Magnetic lines of force tend to follow the path of least opposition**, figure 2-6.

6. **Lines acting in the same direction tend to repel each other,** figure 2-7a, **and lines acting in the opposite direction tend to attract each other,** figure 2-7b.

7. **The magnetic field is most intense where lines are the closest together.**

Flux Density

The number of magnetic lines of force per square centimeter in a plane perpendicular to the direction of the magnetic field is commonly called the *flux density* and is designated by the symbol B. When the magnetic field is uniform, each square centimeter contains the same number of lines of force. The flux density may be expressed as:

$$B = \frac{\phi}{A} \tag{2.1}$$

where B is the flux density in gausses (a gauss represents the flux density of one line per square centimeter), ϕ is the total flux in *maxwells* (one line of force is equal to one maxwell), and A is the area in square centimeters. The terms, magnetic flux and magnetic lines of force, are synonymous.

Since magnetic lines of force must form complete loops, the path these lines of force trace is termed a *magnetic circuit.* The magnetic flux in a magnetic circuit is analogous to electric current in an electric circuit and, as will be shown later, the magnetic circuit will require a source of

magnetomotive force which is analogous to the electromotive force of an electric circuit.

As stated previously, magnetic materials are those which will be attracted to a magnet, but may or may not possess the property of *polarity* or have the power of attracting other magnetic material. In discussing magnetic materials, the most commonly referred to properties are *reluctance, reluctivity, permeance, permeability,* and *retentivity*.

Reluctance is the opposition offered by a material to the passage of magnetic flux. This corresponds to resistance in the electric circuit. The reluctance of a magnetic material varies with the flux density, while the reluctance of nonmagnetic material is constant. The symbol for reluctance is R and no units have been assigned for its unit of measurement.

Reluctivity is the specific reluctance or the reluctance per cubic centimeter. Reluctivity corresponds to resistivity of an electrical material. For nonmagnetic materials the reluctivity is 1. The symbol for reluctivity is r and no unit of measurement has been assigned.

Permeance is the ability of a material to permit the setting up of magnetic lines of force. The symbol for permeance is P and no unit of measurement has been assigned. Permeance corresponds to conductance in the electric circuit.

Permeability is the specific permeance or the permeance per cubic centimeter. The symbol for permeability is μ and no unit of measurement has been assigned. Permeability corresponds to conductivity of an electric circuit.

Retentivity is the ability of a material to retain magnetism after the magnetizing force has been removed. The greatest number of flux lines a material can maintain per cubic centimeter after the magnetizing force has been removed is called the *residual magnetism* or *remanence.* After the magnetizing force has been removed, the demagnetizing force required to reduce the residual magnetism to zero is called the *coercive force.*

It has been common practice to classify materials as either magnetic or nonmagnetic. With the advances of science today, the trend is to classify materials into one of three groups: *ferromagnetic, diamagnetic,* or *paramagnetic.*

Ferromagnetic materials are those materials that have a permeability many times greater than that of free space. The permeability of free space in the CGS system of units is 1. Iron, nickel, cobalt, magnetite, steel, permalloy, and alnico are materials that fall into this category. These materials become strongly magnetized in the direction of the magnetizing field.

Diamagnetic materials are those materials that have a permeability less than free space. Silver, gold, mercury, zinc, copper, antimony, and bismuth are materials that fall into this category. These materials become very weakly magnetized but in a direction opposite to that of the magnetizing field.

Paramagnetic materials have a permeability that is slightly greater than 1. Aluminum, platinum, oxygen, air, manganese, and chromium are materials that fall into this category. These materials become weakly magnetized in the direction of the magnetizing field.

Magnetic materials become nonmagnetic materials when they are heated above a critical temperature known as the *curie temperature.* Devices such as motors, generators, and transformers require strong magnetic properties; therefore, the magnetic materials used must have a curie temperature well above their operating range. Devices such as cathode ray tubes, armature retaining bands, and compass housing, require nonmagnetic materials; therefore, the nonmagnetic materials should be used at temperatures well above the curie temperature to reduce magnetic properties to a minimum.

Magnetic Shielding

Although there is no insulator for magnetic lines of force, it is possible to shield a device from magnetic fields. One means of magnetic shielding is to encase the device in a high permeability (or low reluctance) iron. As the iron will offer a path of low opposition to the flux lines, this will leave the space within the device relatively free of magnetic lines of force. Another method that is used is to encase the device in a material that has a very low reluctance (high permeability). One such material that is used is **mumetal.** The **mumetal** provides high opposition to flux lines and this will leave the space within the device relatively free from magnetic lines of force. The disadvantage of **mumetal** is the extreme care which you must take while working with the metal. Riveting, cutting, or hammering will destroy the low reluctance of the material.

There are three different systems of units in use to measure magnetic effects: the MKS, CGS, and English system. The CGS system is generally utilized in the discussion of magnetic circuits and is used in this discussion. The units of measurement used in dealing with magnetic properties are given in figure 2-8.

			UNITS	
Term	**Formula**	**CGS**	**MKS**	**English**
Flux, ϕ	$\phi = F/R$	Maxwell	Weber	Lines
Flux Density B	$B = B/A$	1 Gauss	Weber/M^2	Kilolines/in^2
Magnetomotive Force F	$F = \phi R$	Gilbert	Ampere-Turn (NI)	Ampere-Turn (NI)
Magnetizing Force H	$H = F/L$	Oersted	NI/meter	NI/in
Reluctance R	$R = F/\phi$	Gilbert/Max	NI/Weber	NI/Kiloline
Permeability μ	$\mu = B/H$	Magnetic Materials 1 for Air or Nonmagnetic Material	Magnetic Materials $4\pi x10^{-7}$ for Air or Nonmagnetic Material	Magnetic Materials 3.2 for Air or Nonmagnetic Material

Fig. 2-8 Units of Magnetic Material Measurement

Some equivalent relationships between the three systems are as follows:

CGS		English		MKS
1 Maxwell	=	1 line of force	=	10^{-8} Webers
1 Gauss	=	6.452 lines/in^2	=	10^{-4} Webers/meters^2
1 Gilbert	=	0.796 NI	=	0.796 NI
1 Oersted	=	2.05 NI/in	=	79.6 NI/meter
1 cm	=	0.394 in	=	10^{-2} Meters
1 cm^2	=	0.154 in^2	=	10^{-4} Meters^2
981 dynes	=	2.2 x 10^{-3} pounds	=	10^{-3} Kilograms
454 grams	=	1 pound	=	0.454 Kilograms

MATERIALS

1 Compass, magnetic

2 Bar magnets

1-1/4" x 1/2" x 1" block of soft iron

1 Ruler graduated in centimeters

Iron filings in a shaker

Glass Plate

PROCEDURE

1. Place a bar magnet on the lab bench with a glass plate over it as shown in figure 2-9.
2. Sprinkle iron filings on the glass and draw the resulting magnetic field pattern.

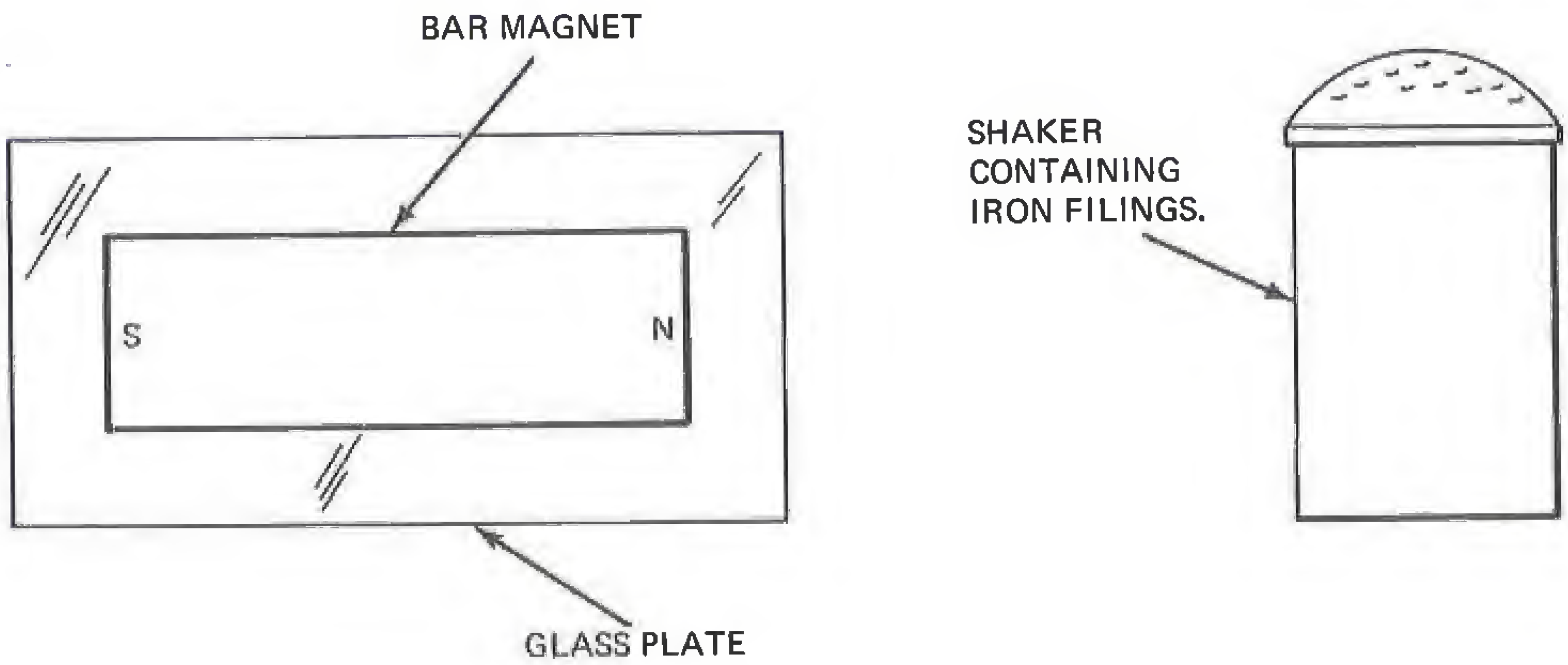


Fig. 2-9 Experimental Set-up I

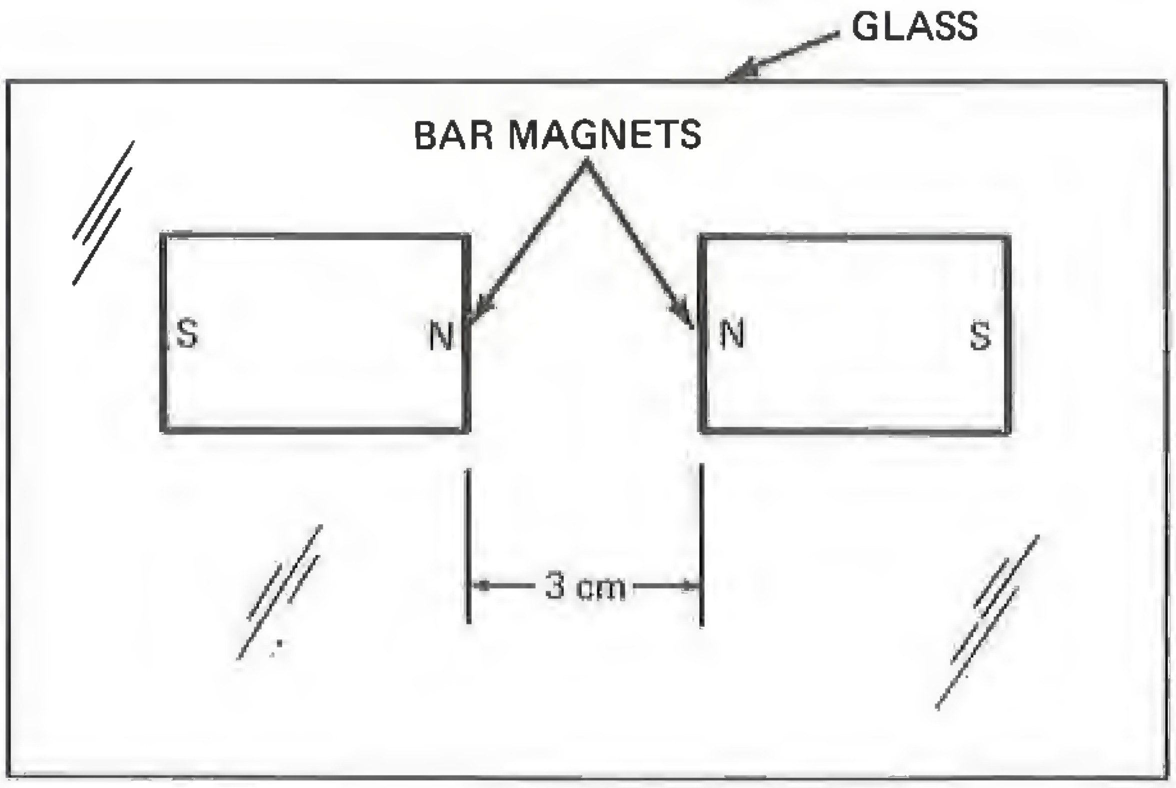


Fig. 2-10 Experimental Set-up II

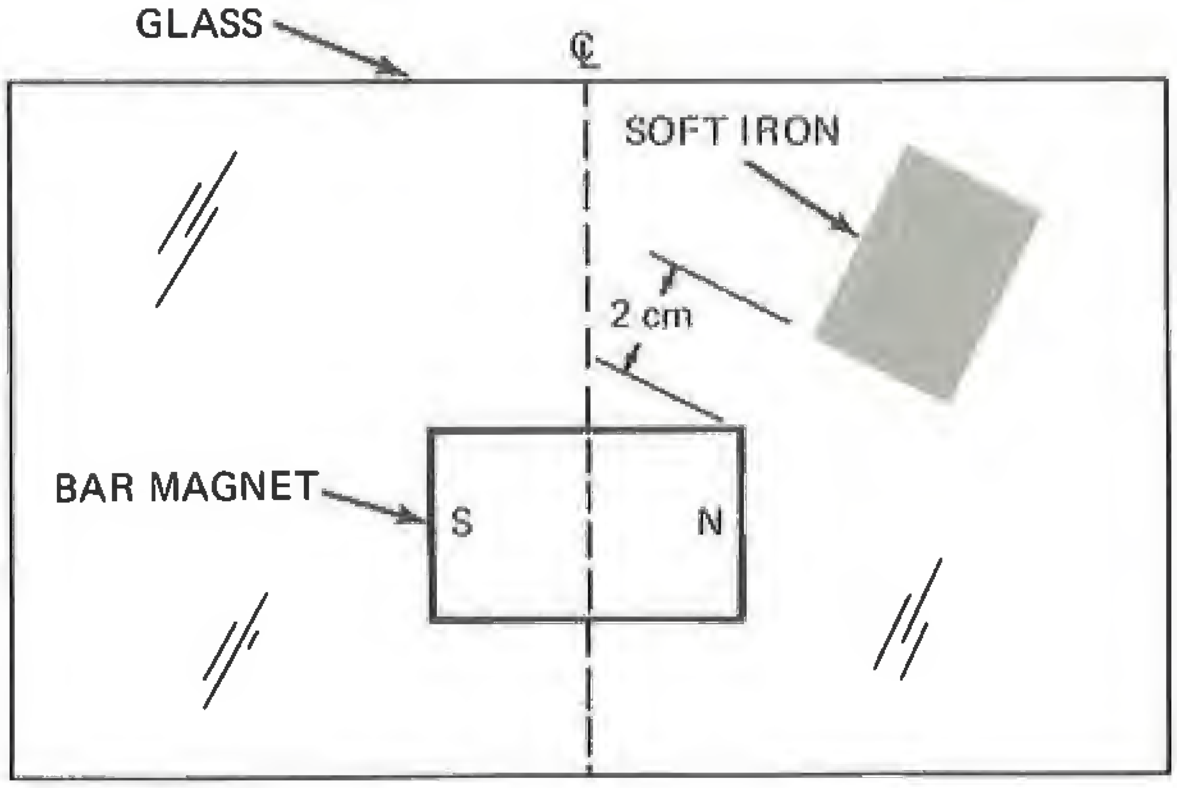


Fig. 2-11 Experimental Set-up III

3. Place another magnet under the glass such that like poles are toward each other as shown in figure 2-10.
4. Sprinkle iron filings on the glass and draw the resulting magnetic field pattern.
5. Repeat steps 3 and 4 but with unlike poles toward each other.
6. With one bar magnet under the glass, place the piece of soft iron under the glass as shown in figure 2-11.
7. Sprinkle iron filings on the glass and draw the resulting magnetic field pattern.
8. With a bar magnet placed on the work bench, move a compass around the magnet as shown in figure 2-12 and chart the direction of the magnetic lines of force.
9. Place the like poles of two bar magnets end to end and observe what happens.
10. Repeat step 9 for unlike poles.
11. Place the block of soft iron on the lab bench as shown in figure 2-13.
12. Carefully slide the magnet toward the soft iron. When the soft iron begins to move, stop! Measure the distance and record in figure 2-15 as configuration 1.

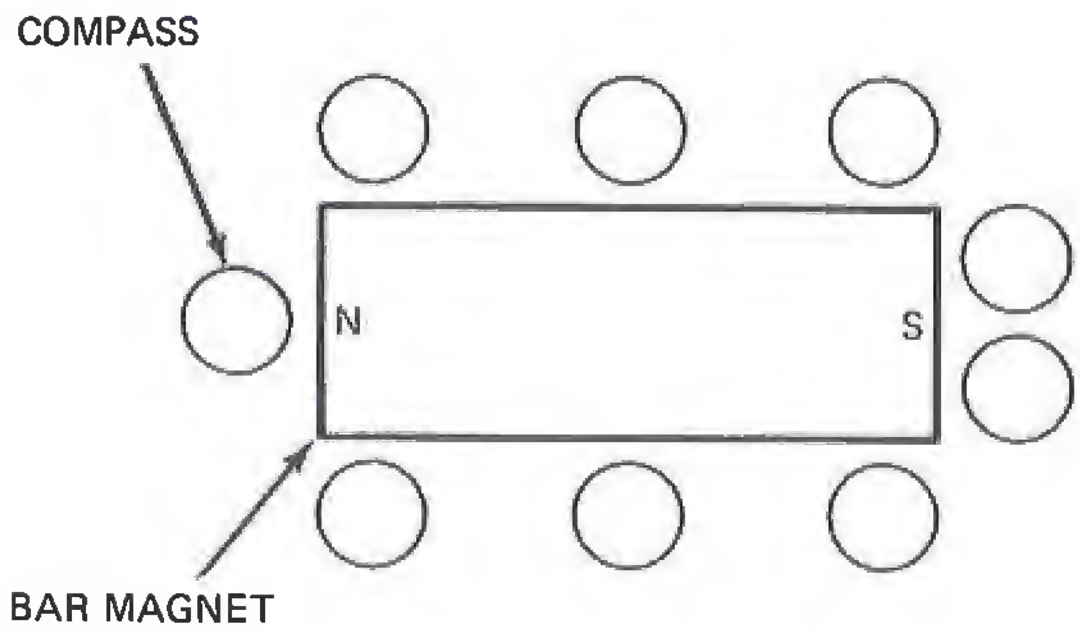


Fig. 2-12 Experimental Set-up IV

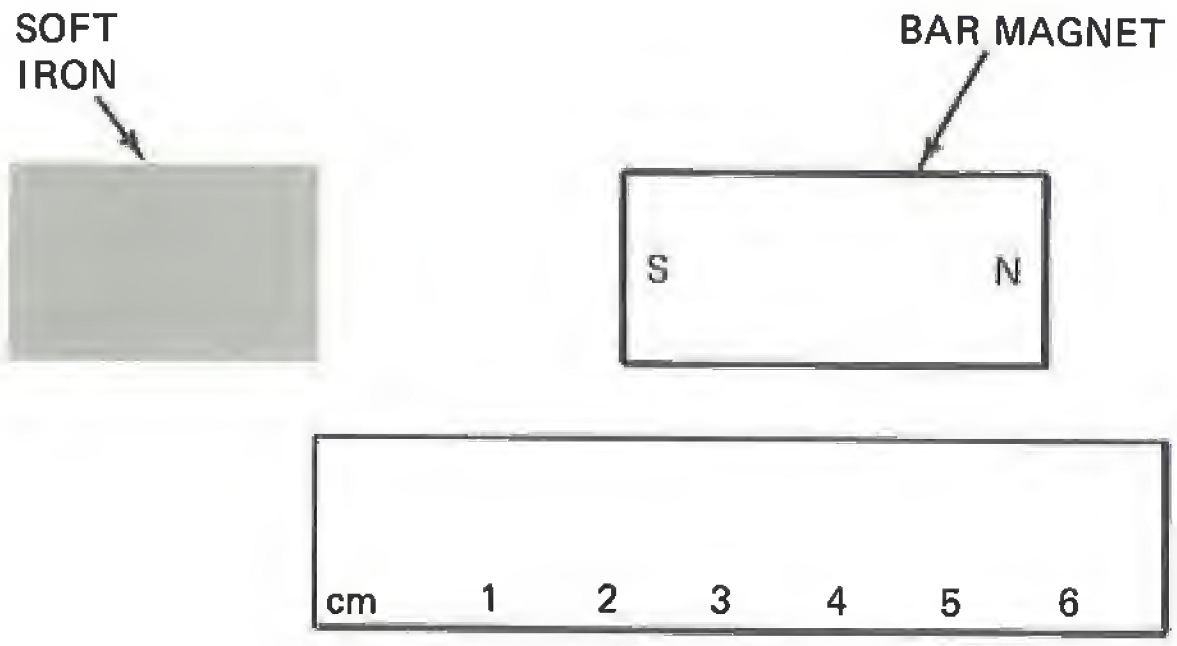
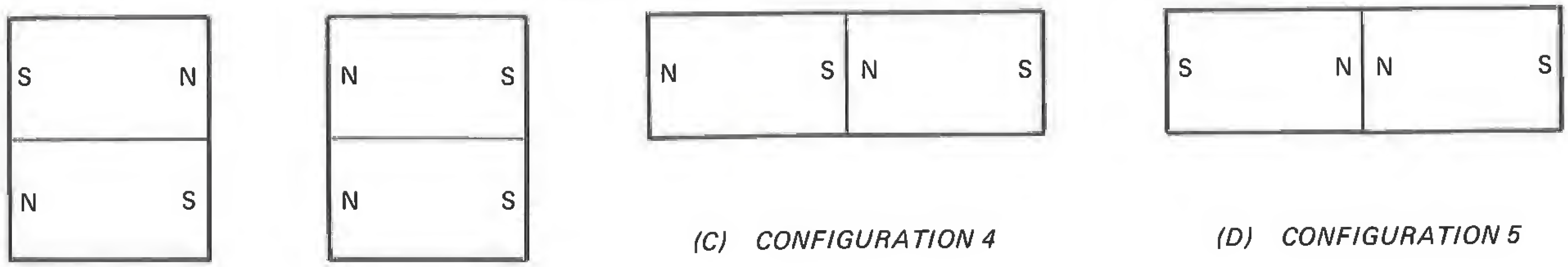


Fig. 2-13 Experimental Set-up V



(A) CONFIGURATION 2 *(B) CONFIGURATION 3* *(C) CONFIGURATION 4* *(D) CONFIGURATION 5*

Fig. 2-14 Experimental Set-up VI

13. Repeat steps 11 and 12 for each of the bar magnet configurations shown in figure 2-14.

Configuration	1	2	3	4	5
Distance in Centimeters					

Fig. 2-15 The Data Table

ANALYSIS GUIDE. In the analysis of the results discuss each of the positions of the magnets by using the six characteristics of magnetism. Explain any other characteristics you may have observed in the experiment.

PROBLEMS

1. A 10-lb. magnet with a north pole strength of 100 unit poles is placed 5 cm from a south pole of a magnet weighing 5 lbs. whose strength is 500 unit poles. What is the force in pounds acting on these poles?

2. The north magnetic pole of a permanent magnet has a total flux of 250,000 lines. If the field is uniformly distributed and the pole is 2 cm wide and 5 cm long, what is the flux density?

3. What is the curie temperature of iron, nickel, and of cobalt?

4. Would a speaker with the heaviest magnet definitely have a stronger magnetic field? Why?

5. If 6×10^{-6} webers pass through an area of 1.2 square meters, find (a) the flux (ϕ) in maxwells and in lines, (b) the flux density (B) in webers/square meter, in gauss, and in lines/sq. in.

6. If you have two identical pieces of iron and one was permanently magnetized and the other was not, how can you determine which of the two is the magnet? Explain.

ANGULAR VELOCITY MEASUREMENT

INTRODUCTION. There are a number of ways in which the *angular speed* of a device can be determined. In this experiment we will examine three common methods of measuring revolutions per minute or *RPMs.*

DISCUSSION. There are a number of RPM counters in use today. An instrument that measures angular speed, as that of a rotating shaft, is a tachometer. Three of the major types are the *mechanical tachometer, electrical tachometer,* and *stroboscope* or *electronic tachometer.* The measurement may be in revolutions over a measured period of time or it may be measured directly in revolutions per minute (RPM). The instrument may also indicate the average speed over a time interval or the instantaneous speed. Tachometers are used either for direct measurement of angular speed or as elements of control to furnish a signal which is a function of angular speed.

The simplest type of instrument is a *revolution counter,* as illustrated in figure 3-1. This counter is used for counting uniform speeds over a measured period of time. The dial shown is simply a counter which indicates the total number of revolutions made.

The *centrifugal tachometer* is actuated by the centrifugal force developed by a rotating mass. The force developed is proportional to the instantaneous speed and is accurate to about ±0.1 percent. Figure 3-2 illustrates this type of tachometer.

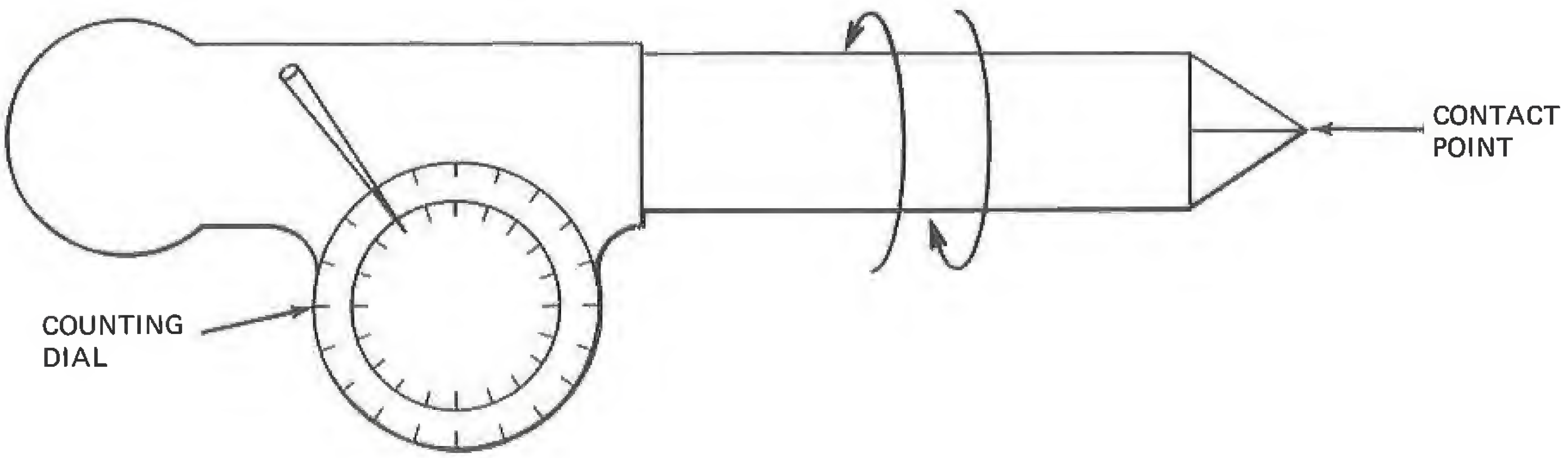


Fig. 3-1 Schematic of a Revolution Counter

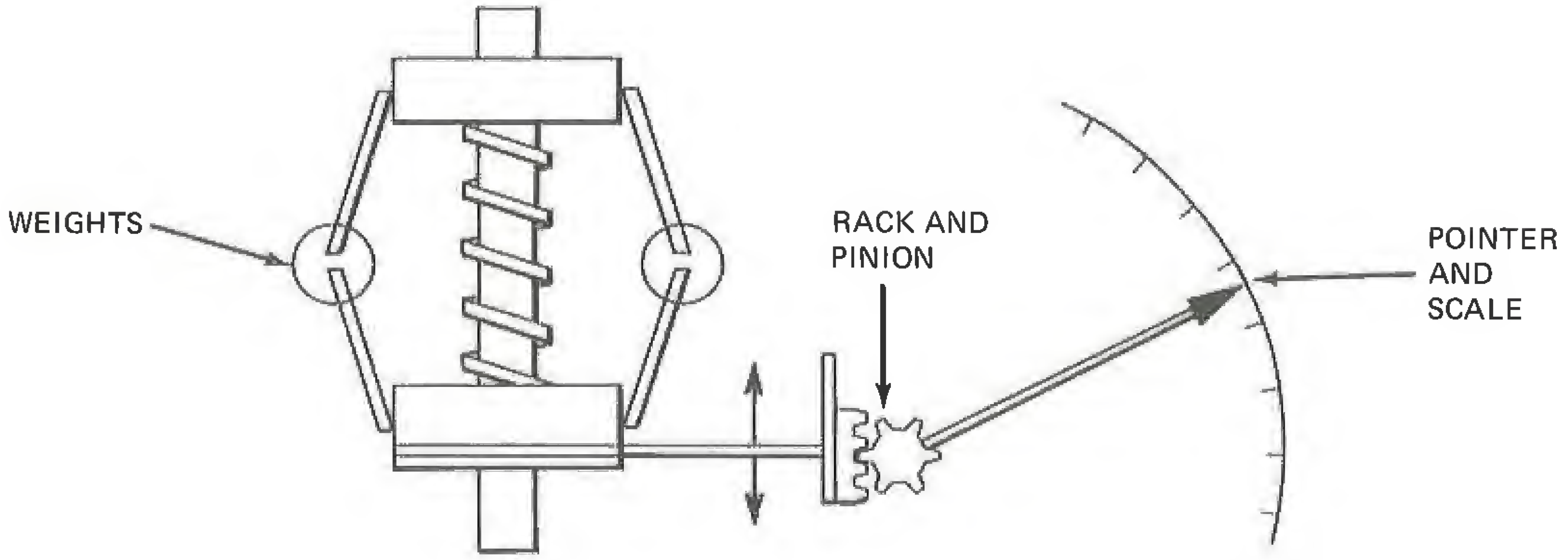


Fig. 3-2 Centrifugal Tachometer

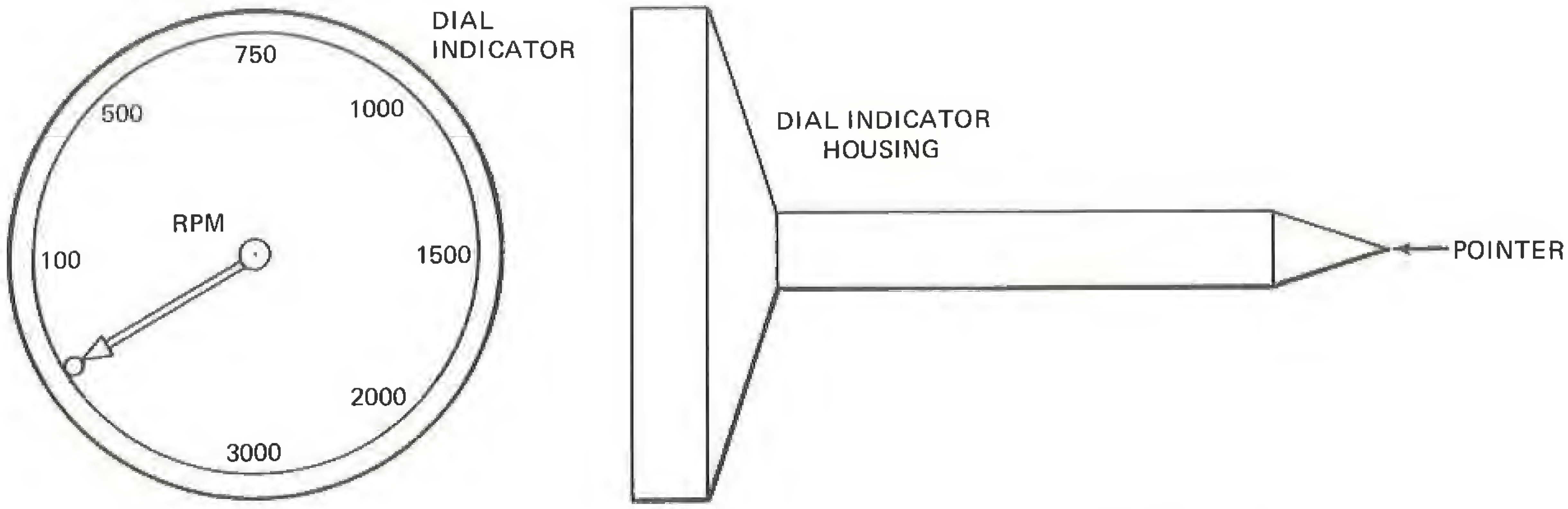


Fig. 3-3 Portable Hand Tachometer

Another mechanical tachometer is shown in figure 3-3. This type is very popular and is inserted onto the end of a shaft or the center of a wheel, and the RPM is measured directly. The pointer is usually rubber-tipped and is connected directly by a shaft to a magnetic or mechanical system inside the dial indicator housing.

Electrical tachometers have a wide range of uses and designs. The electric tachometer is actually a transducer, the most common one being a DC or AC generator. The output is measured with a voltmeter. The RPM is proportional to the voltage output. These instruments are madè with accuracies as high as ±1/2 percent.

The *DC tachometer* shown in figure 3-4 produces a DC voltage proportional to the speed of the armature. The direction of rotation of the generator determines the polarity of the DC voltage and can be determined by using a voltmeter with the zero at the center of the scale.

The *AC tachometer* is similar to the DC tachometer but uses an AC generator and AC voltmeter as shown in figure 3-5. A rotating member of soft iron causes the flux from a permanent magnet to reverse periodically and induces an alternating current in the coil.

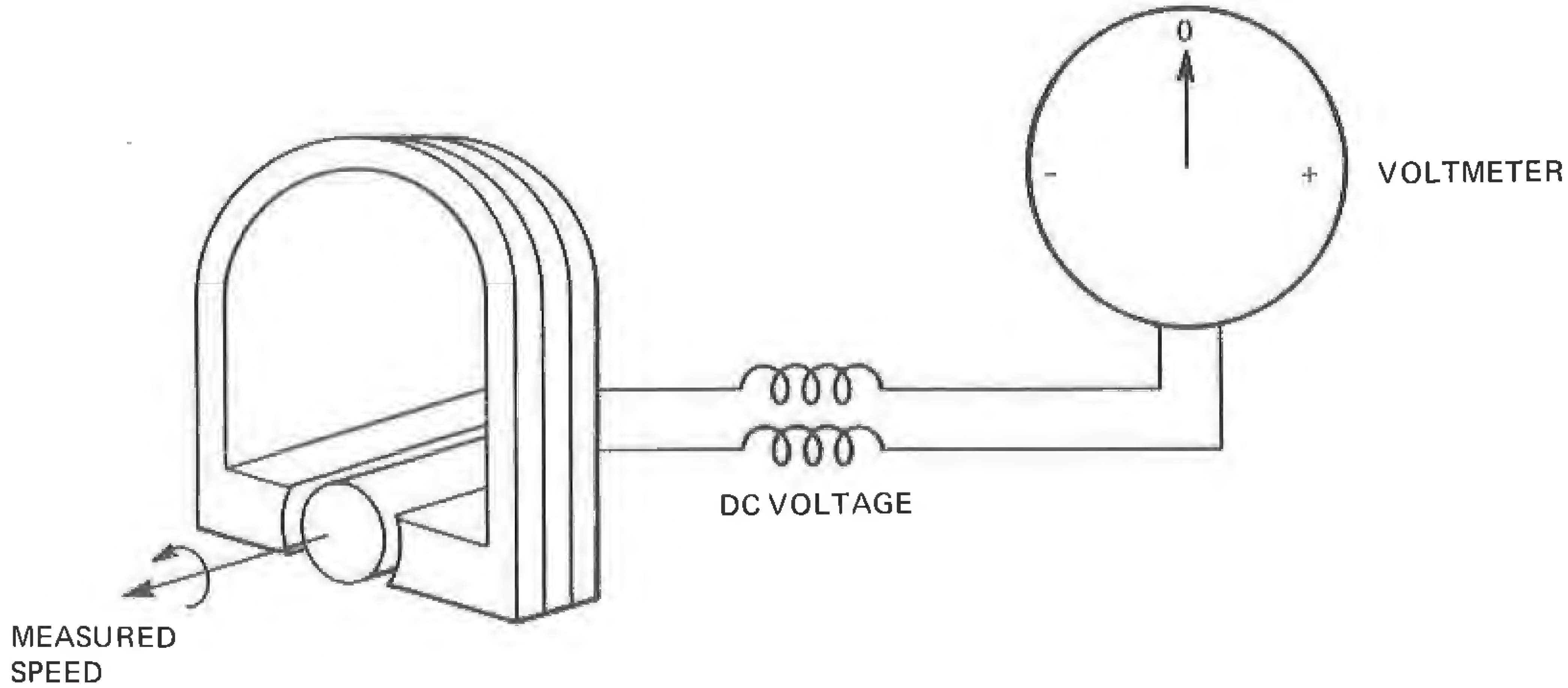


Fig. 3-4 Magnet Generator

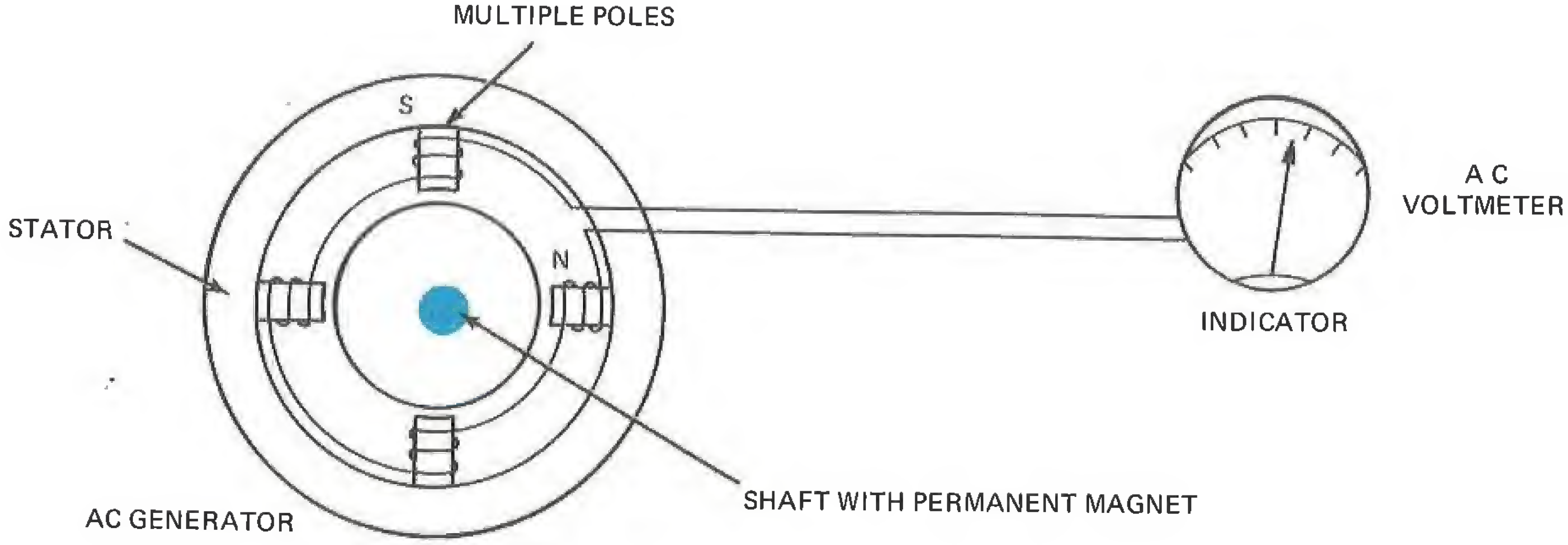


Fig. 3-5 A Schematic of a Basic AC Tachometer

If the output power of the AC generator is high, the use of a pulse-shaping device between the generator and indicator can improve the accuracy of the output. Two common devices used for this purpose are the *saturable transformer* and the *capacitor,* both are shown in figure 3-6. The basic function of the transformer in figure 3-6a is to act as a gate allowing only a part of the energy produced to pass to the indicator. The rest of the energy is retained in the generator. The amount of energy transmitted to the indicator is constant; the value depends on the size of the transformer. The readings are proportional to the frequency of the generator pulse output rather than the output voltage.

The *capacitor-type tachometer,* sometimes called the *impulse* or *current-charging tachometer,* is shown in figure 3-6b. In this instrument the charging current of a capacitor is used. The spindle rotates a pickup head which contains a reversing switch. The rotation causes the switch to reverse twice

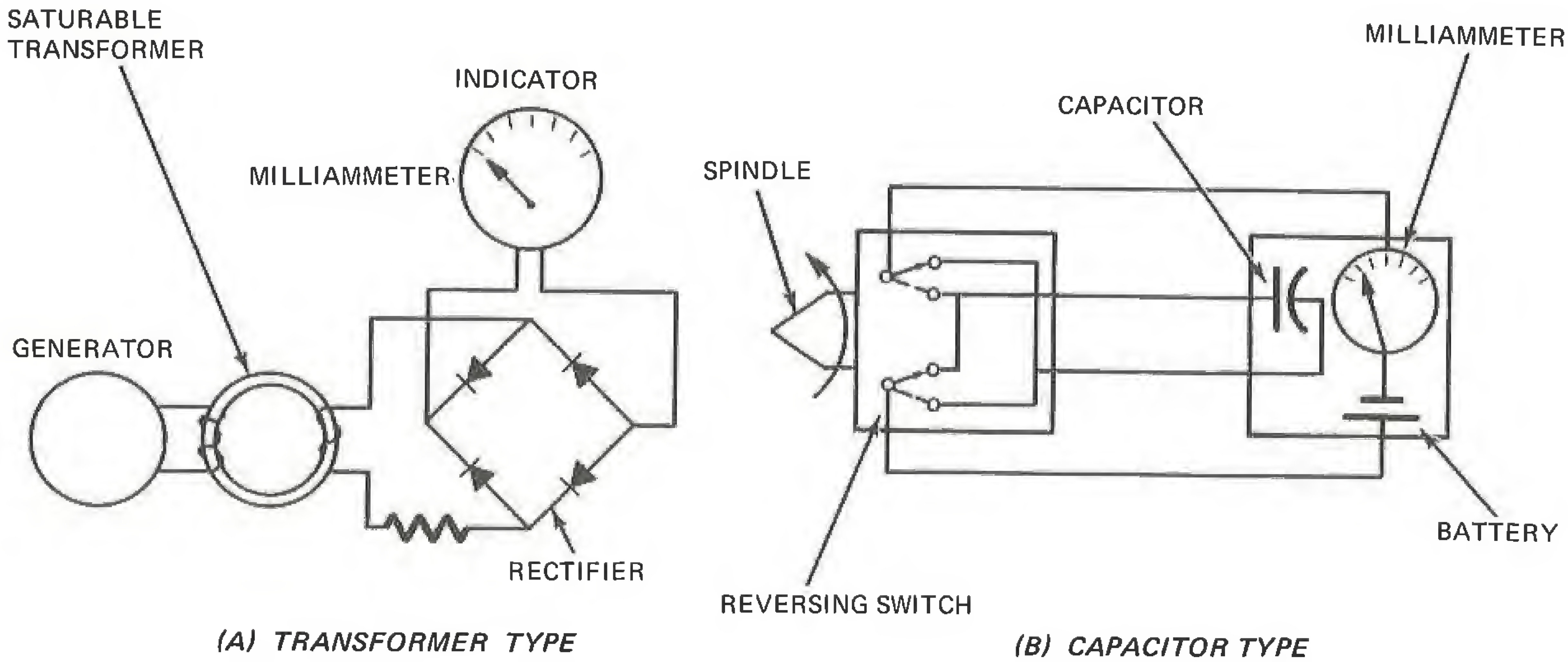


Fig. 3-6 A Schematic of Saturable Transformer Tachometer and Capacitor Tachometer

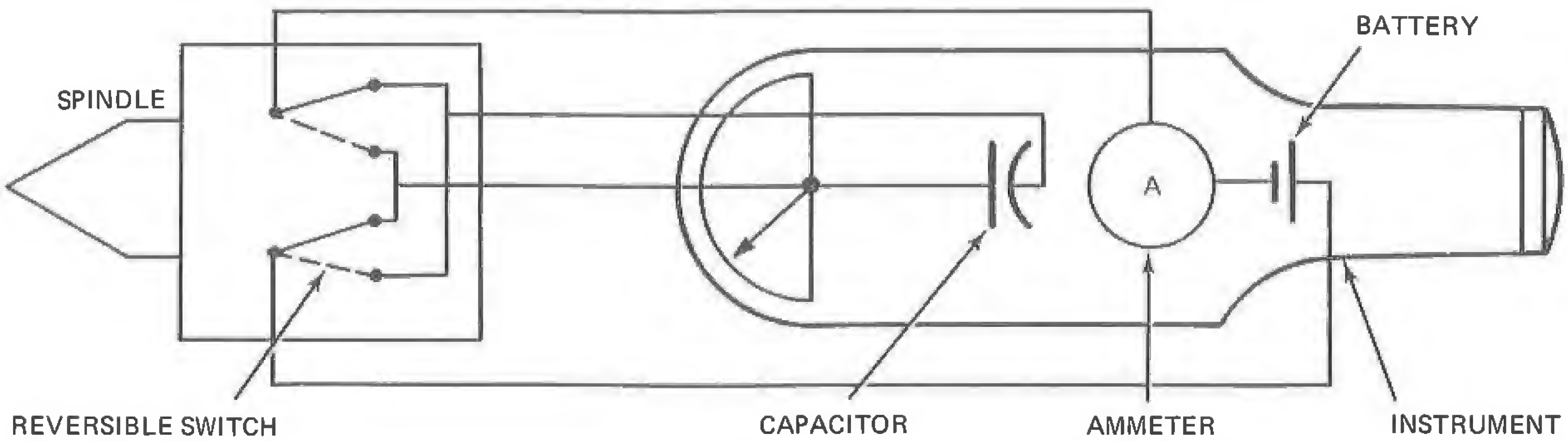


Fig. 3-7 Impulse Type Tachometer

with each revolution. The indicator, as shown in figure 3-7, responds to the average height of each pulse. The indication is proportional to the rate of spindle revolutions.

The *inductor tachometer* shown in figure 3-8 has a piece of soft or laminated iron rotating in a magnetic field. The rise in flux produces a pulse of one polarity and the fall produces a pulse of the other polarity and an AC voltage is generated. This AC voltage is then rectified by a bridge rectifier and causes an indication on the DC milliammeter that is proportional to the speed being measured.

The interrupted type tachometer as shown in figure 3-9 is an example of an *ignition tachometer.* The current from the battery is interrupted by the contactor. This sudden interruption of current excites the ignition coil and the saturable transformer. The output of the saturable transformer is rectified to produce an average current through the DC milliammeter that is proportional to the speed being measured.

The *stroboscope* is another type of tachometer. The principle of the stroboscope is closely allied with the illusion of motion.

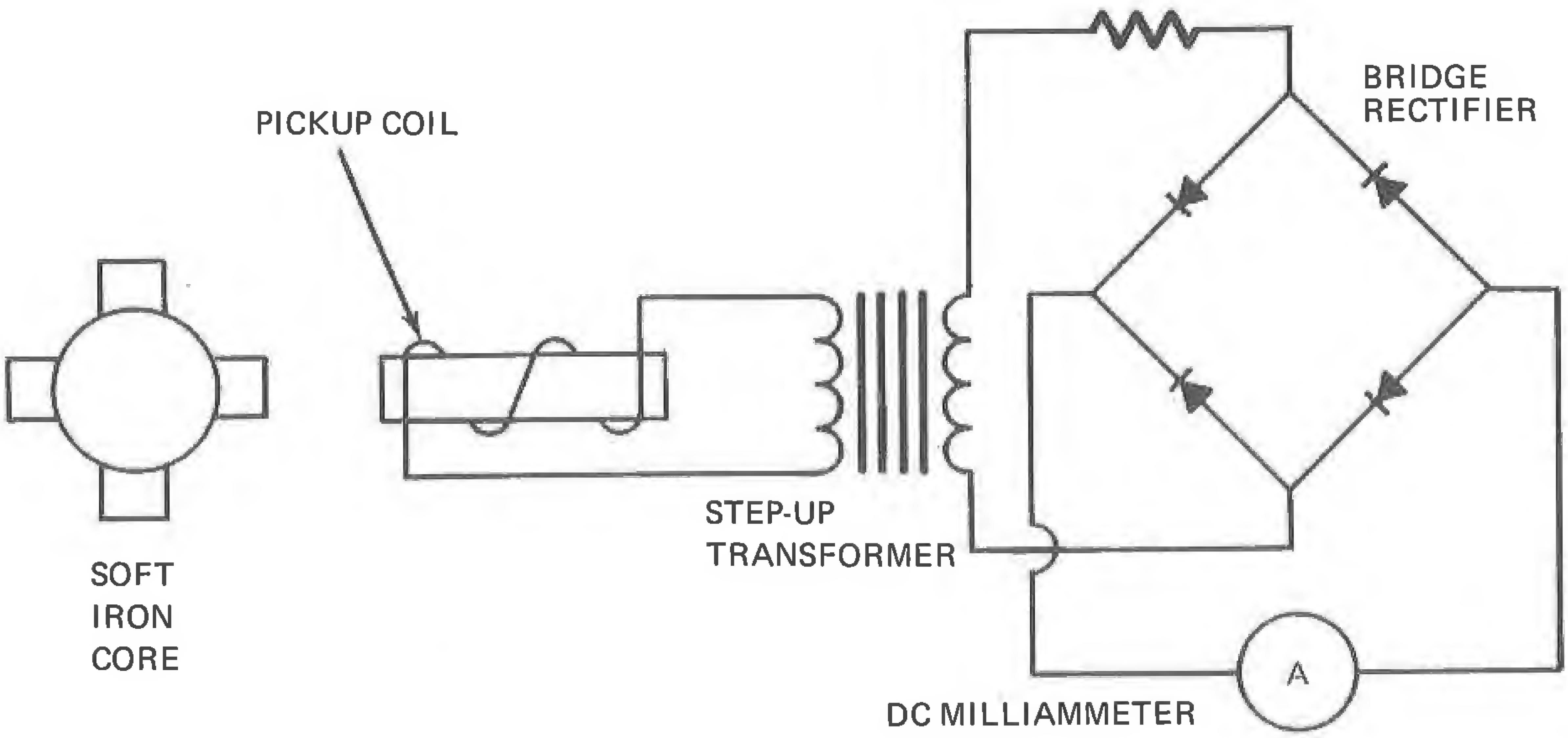


Fig. 3-8 Schematic For An Inductor Tachometer

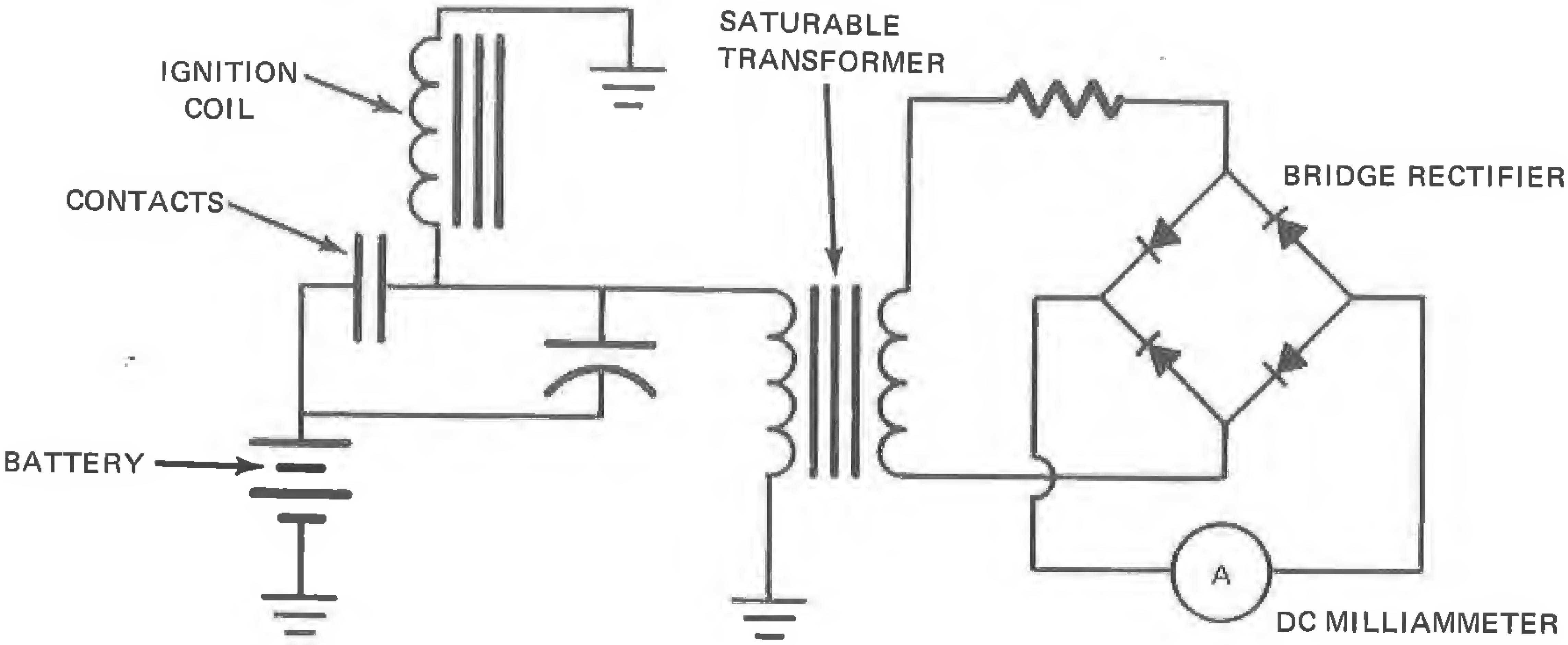


Fig. 3-9 Schematic of an Ignition Tachometer

The motion can be made to appear to stand still by a stroboscope even though it may be rotating several thousand RPM.

The concept of the stroboscope (strobe) dates back to 1830 when Faraday constructed a machine which presented an illusion of arrested motion. The application of the stroboscope to scientific investigations began in the latter half of the nineteenth century when Taylor constructed a vibrating shutter when doing studies of the theory of sound. The modern use of the stroboscope utilizes an intermittent electric discharge in place of a moving shutter. This method is attained by combining a spark gap with a capacitor. As the capacitor charges and discharges, the light flashes off and on. To see how one can use a controlled flashing light to measure speed, refer to the fan blade shown in figure 3-10.

Suppose that the fan is running and the blade is revolving at 1800 RPM. Looking at the blade one will see just a blur because the fan is turning so fast.

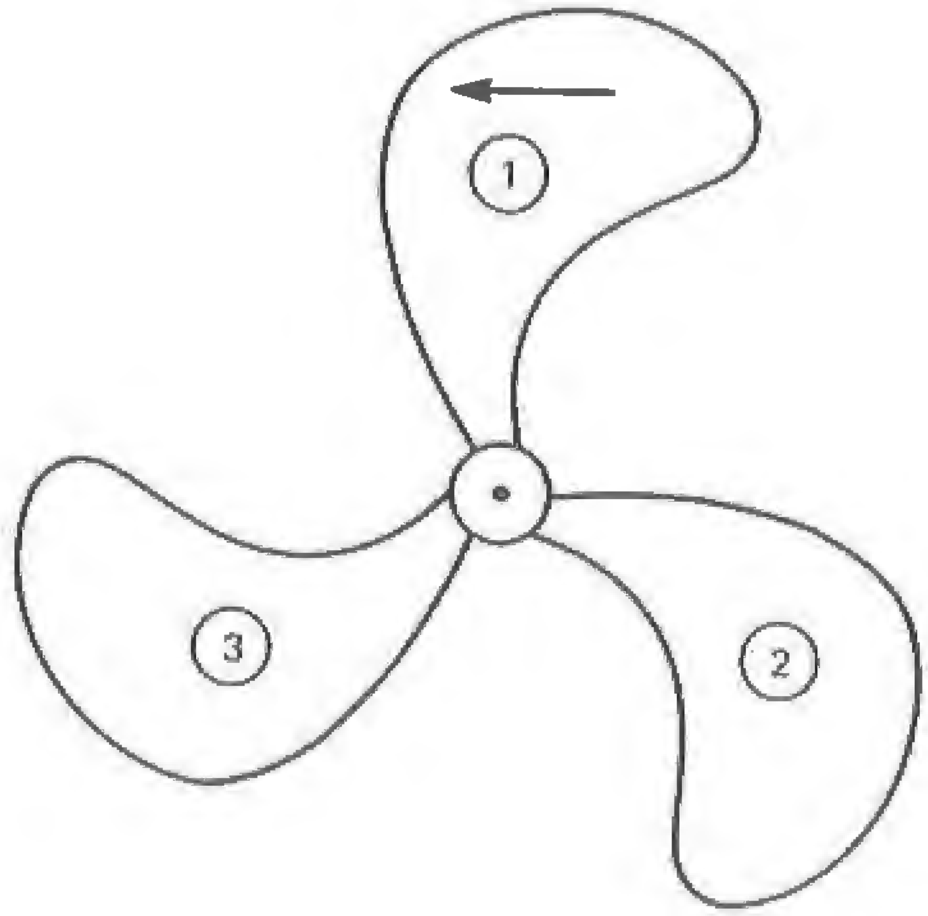


Fig. 3-10 Strobing a Fan Blade

Now, with the strobe light in front of the fan and the flash set at 1800 times a minute, the fan blades will *appear* to stand still. What is happening is that even though the blades are turning they are in the same position every time the light flashes. During the time that the light is off the blades turn one revolution then end up back where they were when the light flashes again.

Consequently, it would seem that all one has to do is adjust the strobe rate until the fan appears to stand still. Then read the speed in RPM on the scale of the stroboscope.

There are, however, a couple of things to be considered. The fan in figure 3-10 has three blades which look alike, so if the flash is 5400 times a minute (3 X 1800), the blades will appear to stand still. This happens because one "sees" the blades every 1/3 of a revolution and since the blades are alike he can't tell that he is seeing a different blade each time. This difficulty can easily be cured by marking one of the blades with a scratch or a piece of tape. Then if the mark stands still one knows the strobe isn't flashing too fast.

Going the other way, if the strobe is set to flash 900 times a minute (1800 X 1/2) the marked blade will turn two revolutions between flashes and will appear to stand still. Similarly, it will appear to stand still at 600 flashes (1800 X 1/3), 450 flashes (1800 X 1/4), 360 flashes (1800 X 1/5), 300 flashes, etc. per minute.

To avoid this problem one must be sure that the flash rate of the stroboscope is set to the highest possible value which will cause the marked blade to stand still.

Once in a while it is difficult to be sure that one has the highest possible flash rate that will make the mark stand still. In such a case the *highest available reading* which makes the mark stand still is used. Since it is known that this reading is some angular velocity, call this reading ω/x. Then slowly and carefully reduce the flash rate to the *next lower reading* which is the next smaller integral fraction of ω and is equal to $\omega/(x+1)$. Next take the product of these two readings and divide it by their difference,

$$\boxed{\frac{\text{(highest available reading) X (next lower reading)}}{\text{(highest available reading)} - \text{(next lower reading)}}}$$

This algebraically gives

$$\frac{\left(\frac{\omega}{x}\right)\left(\frac{\omega}{x+1}\right)}{\frac{\omega}{x}-\frac{\omega}{x+1}} = \frac{\frac{\omega^2}{x^2+x}}{\frac{\omega x+\omega-\omega x}{x^2+x}} = \frac{\omega^2}{\omega} = \omega \qquad \textbf{(3.1)}$$

which is, of course, the actual value of the angular velocity.

For example, suppose that 900 flashes per minute was the highest reading we could get with stroboscope and the fan discussed above. Slowly reduce the strobe rate carefully until the next lower reading which causes the marked blade to stand still. This reading would be 600 flashes per minute. Then calculate the angular velocity.

$$\omega = \frac{(900) \text{ X } (600)}{(900) - (600)} = \frac{540{,}000}{300} = 1800 \text{ RPM}$$

This technique is quite useful, but since it is rather involved it should only be used when the *highest possible value* of flash rate cannot be found.

Finally a word of caution — DON'T FORGET THAT A STROBOSCOPE DOES NOT STOP ROTATION — it only makes it look stopped. **Don't try to touch a rotating mechanism when it is being strobed.**

For the purposes of this experiment the student will use three different methods of measuring the angular velocity of a rotating shaft.

MATERIALS

1 Universal motor (28V, 7000 RPM)

1 Variable power supply (0-30 Volts DC)

1 Mechanical Portable Hand Tachometer (0-10000 RPM)

1 DC Generator Tachometer

1 Stroboscope (50-25000 RPM)

1 Mechanical Breadboard

PROCEDURE

1. Connect the motor as shown in figure 3-11.

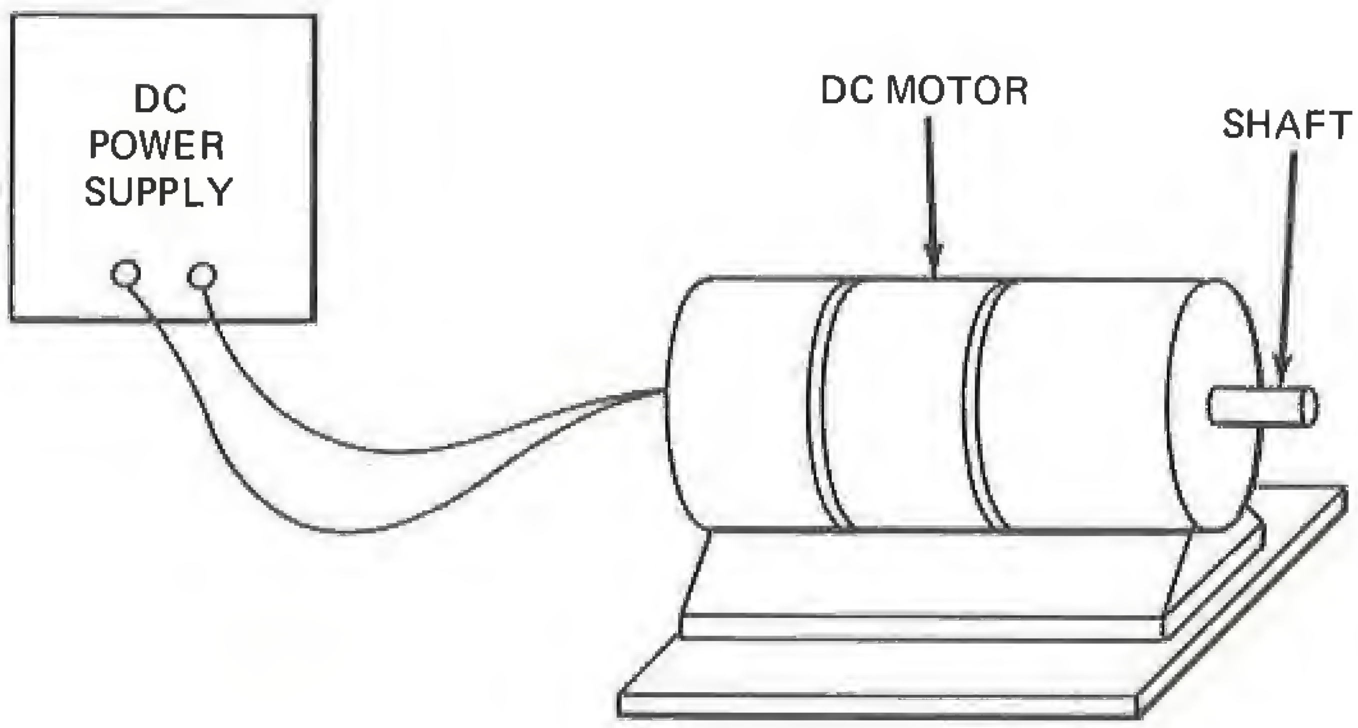


Fig. 3-11 Electromechanical Apparatus Set-Up

2. Couple the mechanical tachometer to the motor shaft and apply 5 volts.
3. Record the RPM in data figure 3-12 at 15-second intervals for one minute.
4. Repeat step 3 for 10, 15, and 20 volts.

TIME	REVOLUTION PER MINUTE (RPM)			
15 sec.				
30 sec.				
45 sec				
1 min.				
Average RPM				
Volts	5V	10V	15V	20V

Fig. 3-12 Volts – RPM Data for Mechanical Tachometer

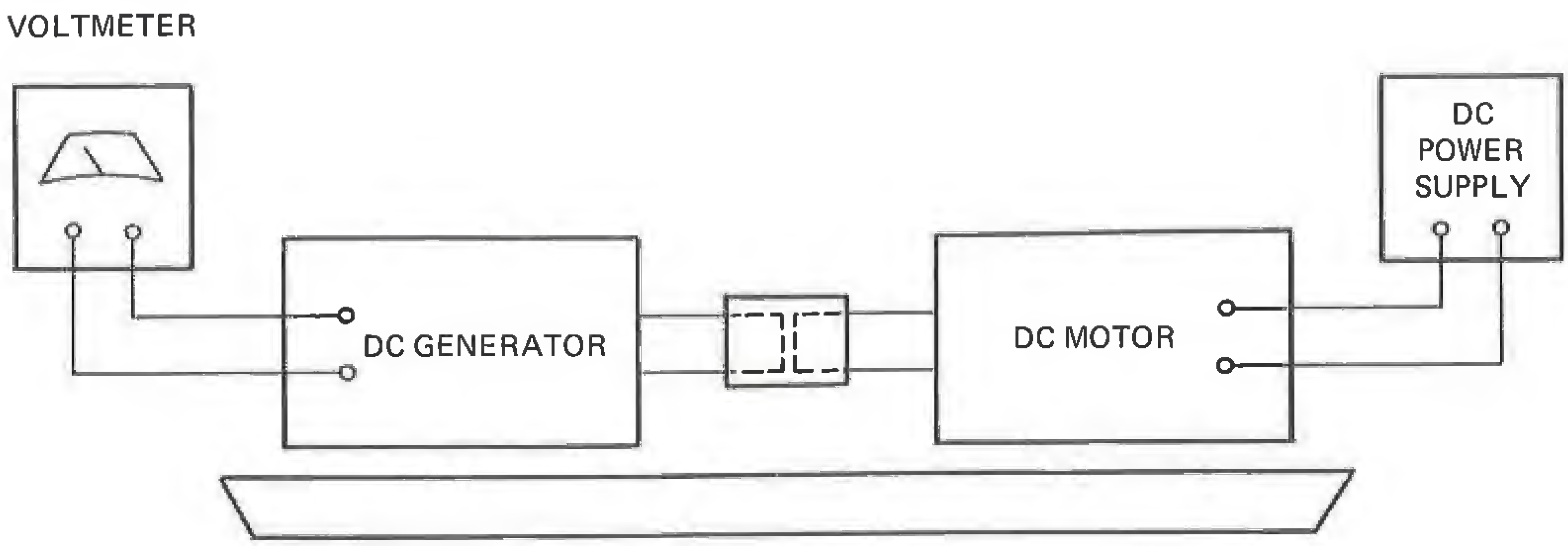


Fig. 3-13 DC Generator Tachometer Set-Up

5. Connect the DC Generator Tachometer as shown in figure 3-13.
6. Increase the motor voltage in 5 volt steps.
7. For every 5 volts applied to the motor, record the voltage produced by the generator in figure 3-14.
8. Complete figure 3-14 by dividing the recorded voltage by the constant voltage per RPM output of the generator.

GENERATOR VOLTAGE/RPM					
Motor Voltage	15	10	15	20	25
Generator Output (Volts)					
Motor RPM					

Fig. 3-14 Volt—RPM Data Table for DC Generator Tachometer

9. Make a mark with a piece of chalk on the motor shaft.
10. Increase the voltage to three volts.
11. Adjust the strobe light to the motor shaft.
12. Increase the voltage in 3-volt steps.
13. Adjust the strobe flash so that the motor appears to be standing still.
14. Record the reading for each 3-volt step in figure 3-15.
15. Plot a graph of the data recorded in the three data tables. For figure 3-12, use the average RPM for each value of voltage.

Readings	1	2	3	4	5	6	7	8	9	10
Volts										
RPM										

Fig. 3-15 Volts — RPM Data Table for Stroboscope

ANALYSIS GUIDE. From the graphs produced one should see a relationship between motor voltage and motor speed. Also one of the speed measuring devices is a better method to use than the other two. Which one do you think is the best?

PROBLEMS

1. If a revolution counter records 1500 revolutions in 20 seconds, determine the RPM.
2. A motor turns 1725 RPM. How many revolutions does it turn per second, per hour?
3. The volts per RPM in an electrical tachometer is .05 volts. What is the RPM if the voltage is increased to 30?
4. If the flash rate of a strobe light is 2000 fpm and the shaft speed of a motor is 6000 RPM, what are the revolutions per flash?
5. What is the true shaft speed of a motor if the lower flash point is 1500 and the upper flash point is 2000?

experiment 4 MOTOR NO-LOAD TEST

INTRODUCTION. In the modern age of technology one of the most used pieces of electrical apparatus is the electric motor. In this experiment we will examine some of the characteristics of the electric motor.

DISCUSSION. Usually for any piece of electrical equipment to be useful it must produce some kind of output. When there is an output there is always an *opposition.* This opposition may be the result of *friction* between moving mechanical parts, resistance to *electrons* flowing in a circuit, friction of a *fluid* moving through a pipe, restriction of air moving through a valve, restriction of heat energy moving through an insulating material, or the reluctance of a material to the establishment of magnetic lines of force. Whenever there is opposition, some form of energy is transferred into another form, usually heat. The effect produced by this opposition is usually not of a usable form, except in heating systems, and is considered to be a loss. It is more commonly known as a *power loss.*

Putting a load on a motor produces losses which are not of a usable form. But before getting into the losses of a motor due to the real opposition present within the motor, a look at the electric motor is in order.

There are a number of different types of electric motors available, but all have essentially the same components: a *rotor, stator,* and *housing.* Because the DC motor is easier to understand than the AC motor, the DC motor will be discussed at this time. Figure 4-1 shows a basic DC motor.

The DC motor works on the principle that when a current is passed through a wire loop which is in a magnetic field, a *torque* is produced on that wire. The magnetic field can be produced by either a permanent magnet or a coil of current-carrying wire wrapped around iron poles. The stationary field assembly is known as the *stator.*

Rotating within the stator is the rotor. The rotor may consist of a current-carrying coil and a *commutator.* When there are a number of coils rotating in the magnetic field, these coils are usually imbedded in slots cut into the outside of a cylindrical iron structure. This iron structure is known as the *rotor.* The commutator is the device by which the current is brought to the rotor.

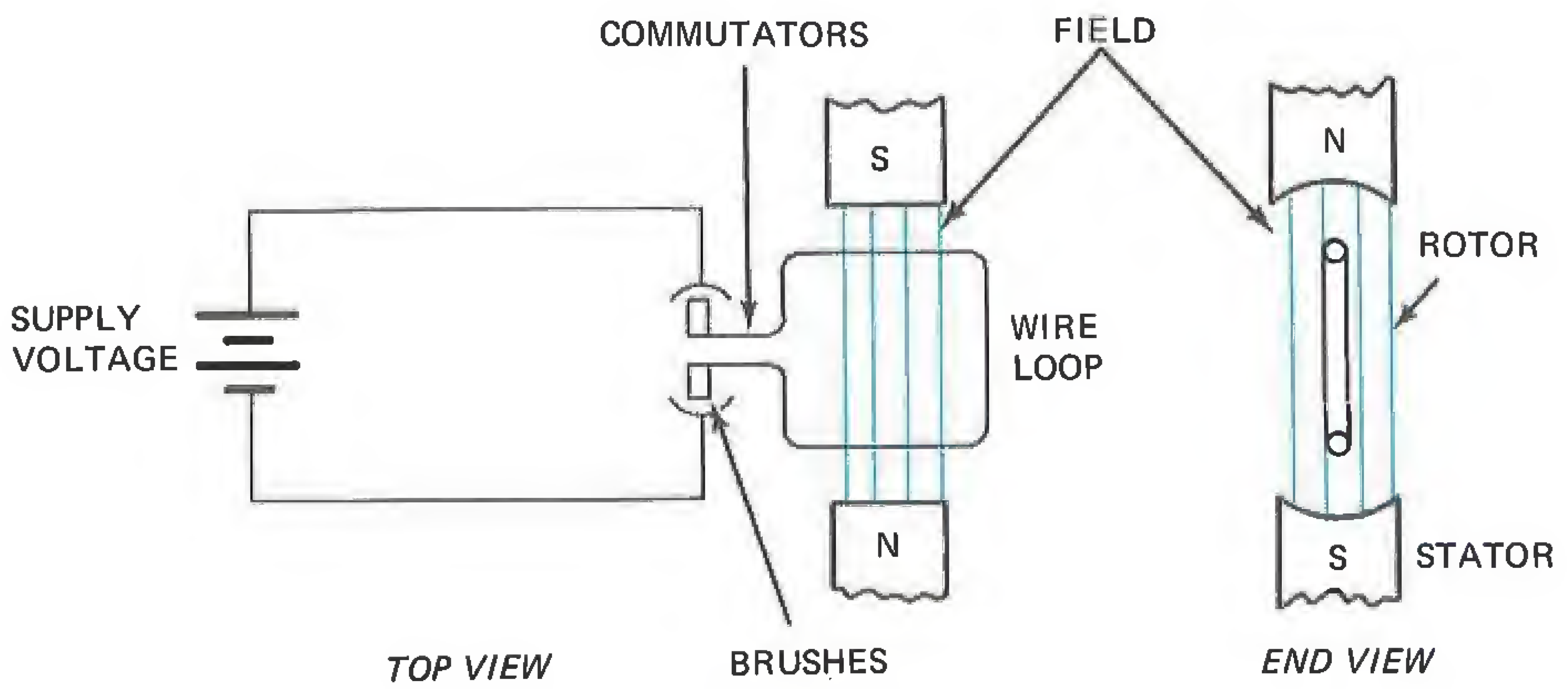


Fig. 4-1 Simple DC Motor

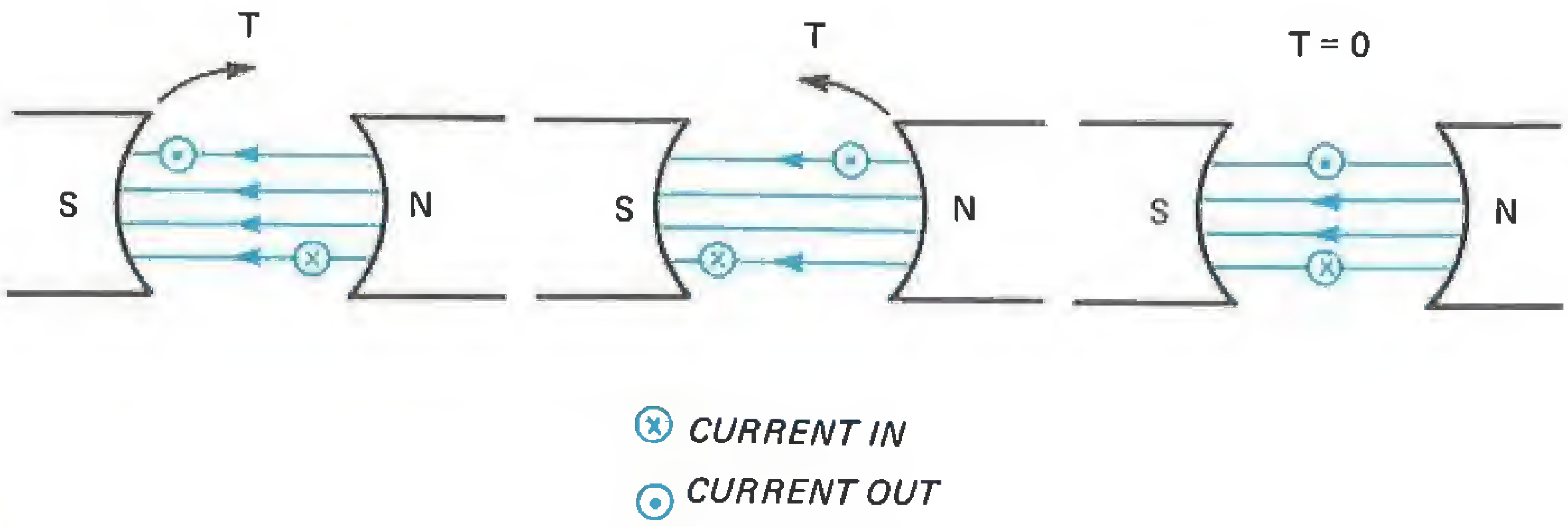


Fig. 4-2 Torque Produced by a Current-Carrying Wire in a Magnetic Field

The torque which a magnetic field exerts on a current-carrying loop of wire disappears when the loop turns so that its plane is perpendicular to the field direction. If the loop swings past this position the torque on it will be in the opposite direction, and will return the loop to the perpendicular orientation. Figure 4-2 shows this schematically.

In order to construct a motor capable of continuous rotation, the current in the loop must be automatically reversed each time it turns 180°. The reversing mechanism is accomplished through the use of a split metal ring and two graphite rods known as *brushes*. Figure 4-5 shows this current reversing mechanism.

Current from the battery enters the rotor (or armature) by means of one of the carbon brushes which makes contact with one-half of the slip ring commutator. The current returns to the battery from the armature by way of the second brush which makes contact with the other half of the commutator. Since the brushes remain fixed while the commutator rotates, each brush is in contact with one-half of the commutator during one half-turn and with the opposite half of the commutator during the second half-turn. As a result, the current in the armature reverses its direction every half-turn and provides the necessary conditions to keep the armature rotating.

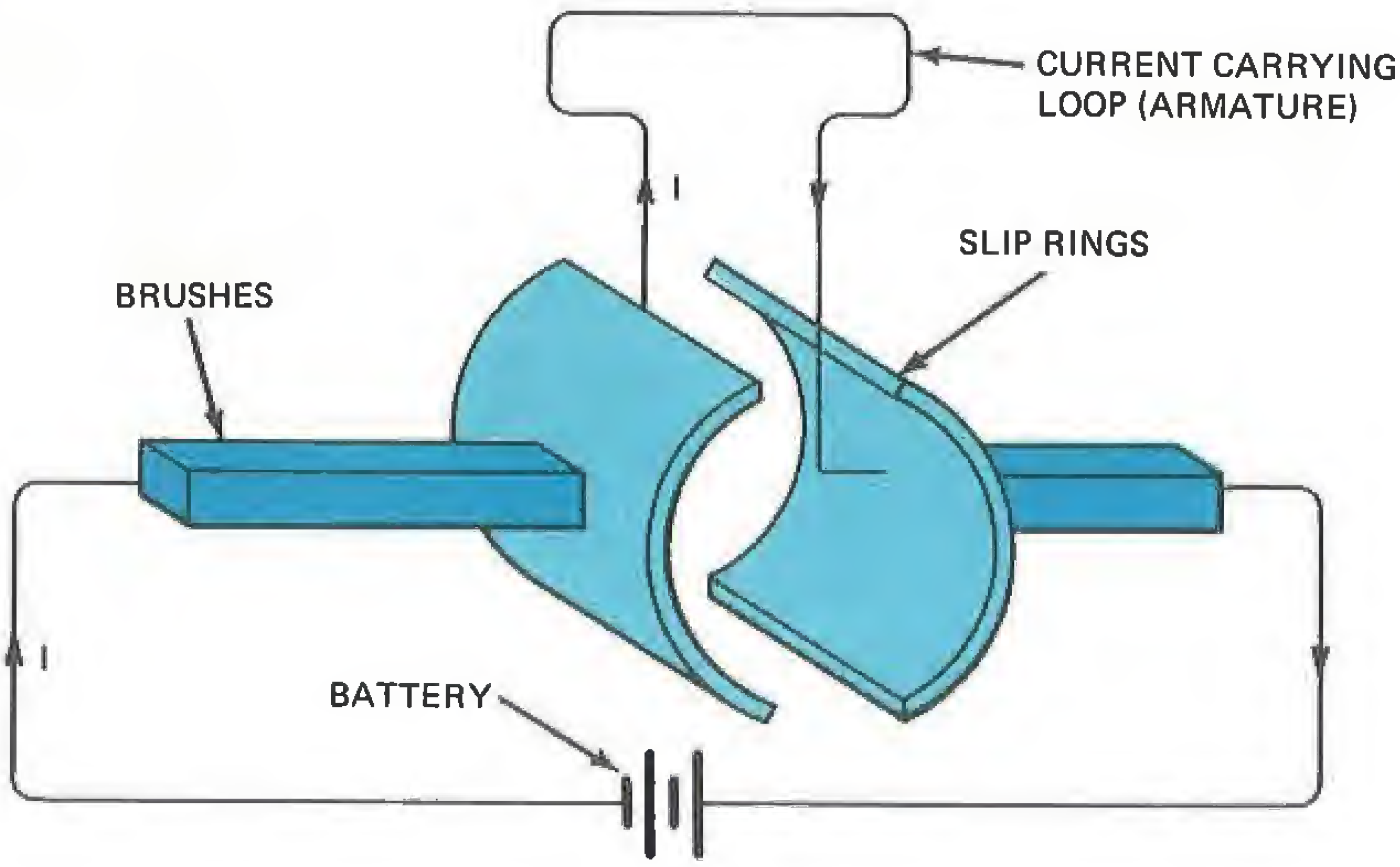


Fig. 4-3 Slip Ring and Brush Assembly

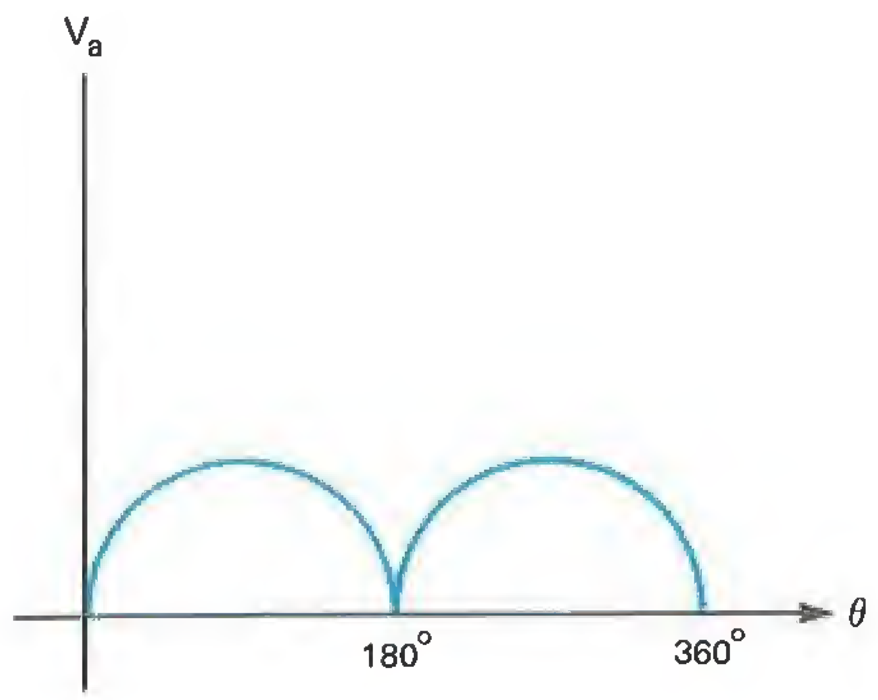


Fig. 4-4 Input to DC Motor With Two Slip Rings

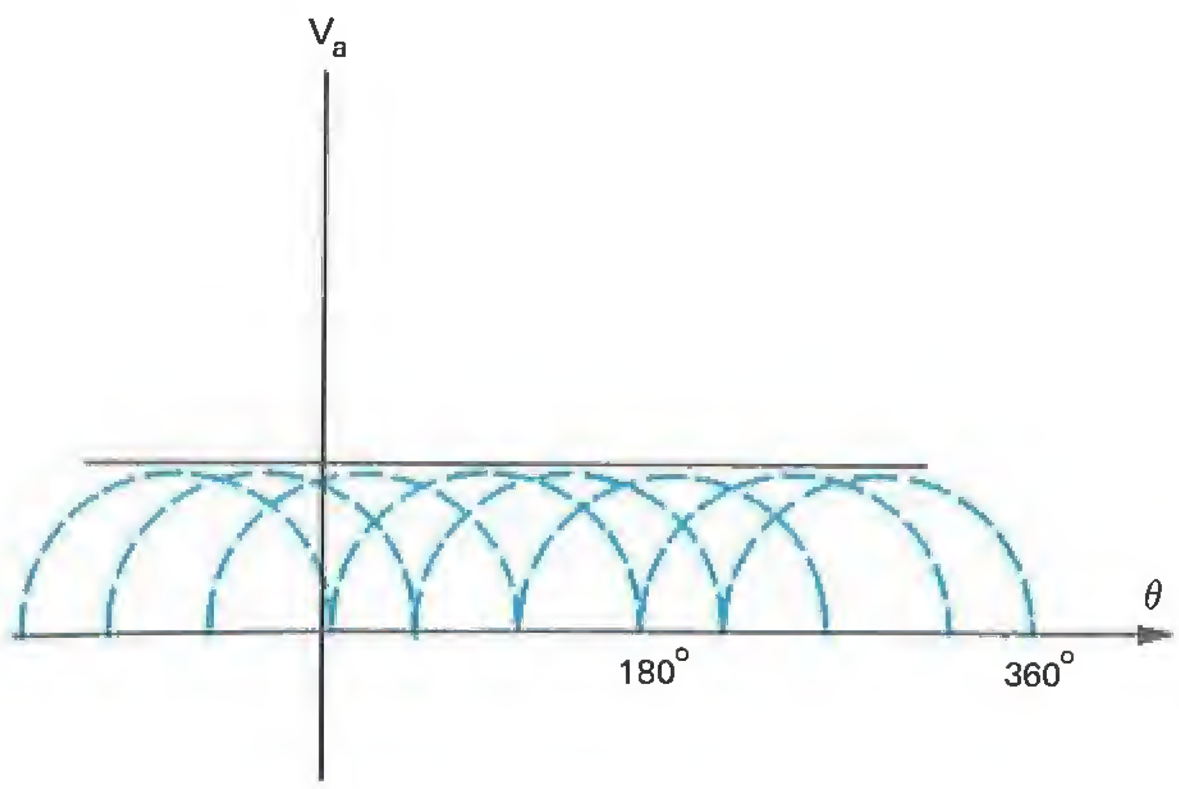


Fig. 4-5 DC Motor Voltage with Several Commutator Segments

By suitably positioning the brushes, the switching takes place whenever the induced voltage tends to change sign, and an induced voltage like that shown in figure 4-4 is obtained.

The voltage fluctuation shown in figure 4-4 can be eliminated by placing more loops of current carrying wire in the armature. With the addition of loops to the armature, more slip ring segments are needed. The commutator assembly is made up of all the slip ring segments. With a commutator of numerous segments, the voltage of the armature might look like the figure 4-5.

The *electromagnetic torque* (T) developed in a DC motor is proportional to the *armature current* (I_a) and the effective *flux per pole* (ϕ_p). The torque is given by:

$$\boxed{T = K\phi_p I_a} \quad \textbf{(4.1)}$$

where I_a = armature current
ϕ_p = flux per pole
K is a constant

$$K = \frac{PZ}{2\pi a} \quad \textbf{(4.2)}$$

where P = the number of poles
Z = number of conductors in the armature winding
a = number of parallel current paths through the winding

To produce a high torque, an end view of an armature with many turns might look like figure 4-6.

As figure 4-6 shows, a number of conductors can be wound on the armature. According to equation 4.2, the more conductors in the armature winding, the greater is the value of K, and as K increases, so does the torque. Also, the larger the conductors used in the armature or the more parallel current paths, the greater will be the current-carrying capabilities of the armature, thus increasing the torque even more.

Torque is also directly proportional to the flux per pole and the number of poles can be added to the motor as long as they are added in pairs, one being north and the other south. The poles may be furnished by permanent magnets or by electromagnets. To increase the flux per pole, the field current to the electromagnet would have to be increased or the strength of the permanent magnet would have to change. Because electromagnet motors get into more involved motor theory, the permanent magnet motor only will be used in this experiment.

The torque of a motor is produced by the action of the magnetic field force on the armature conductors. Since torque is a movement of force, it may be calculated as follows:

$$\boxed{T = Fr} \quad \textbf{(4.3)}$$

where T is the torque in lb-ft, F is the force in pounds, and r is the radius in feet through which the force acts. Figure 4-7 shows this relationship for two rotating arms.

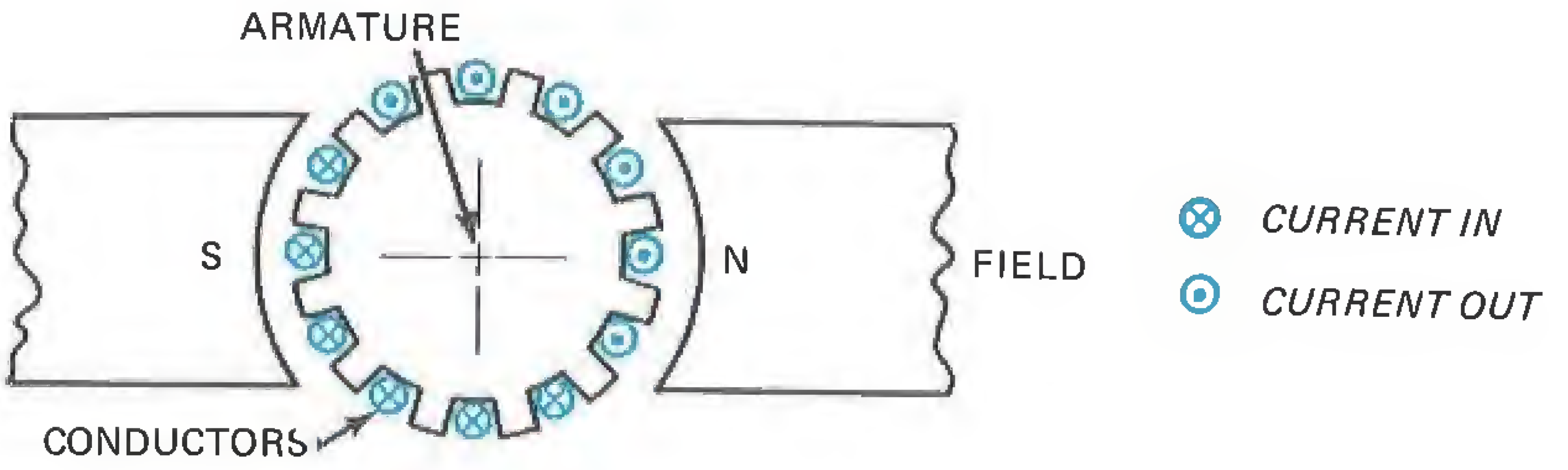


Fig. 4-6 End View of an Armature

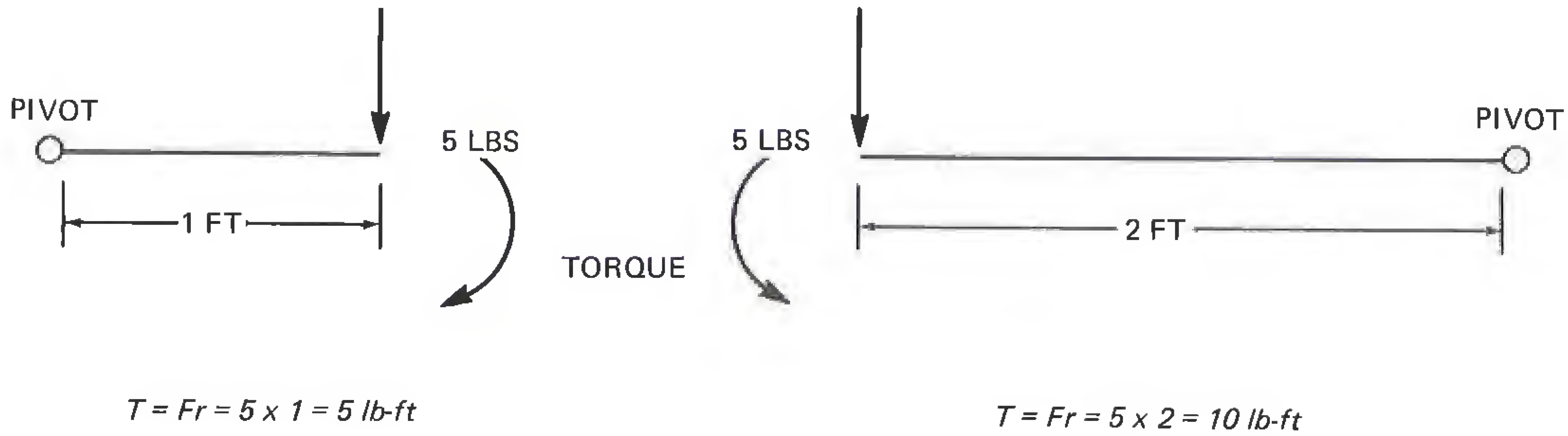


Fig. 4-7 Force — Torque Relationship

Work is another term used when dealing with motors. Work input is defined as the effort involved in moving an object times the distance the object is moved. Work output is defined as the resistance encountered in moving an object times the distance through which the object is moved. In an ideal machine, work is neither gained nor lost. The work output is exactly equal to the work input. Work can be expressed as

$$\boxed{W = Fd} \qquad \textbf{(4.4)}$$

where W = work in ft-lbs
F = force in lbs
d = distance in ft

Power is the time rate of doing work and is expressed mathematically as:

$$\boxed{P = \frac{\text{Work}}{\text{Time}} = \frac{W}{t}} \qquad \textbf{(4.5)}$$

The distance that a rotating shaft travels when delivering power is equal to one revolution ($2\pi r$) times the number of revolutions traveled.

$$d = (2\pi r) \times \text{number of revolutions} \qquad \textbf{(4.6)}$$

Combining equations 4.4, 4.5, and 4.6 we have

$$P = \frac{W}{t}$$

$$P = \frac{Fd}{t}$$

$$P = \frac{F(2\pi r)\ (\text{number of revolutions})}{\text{minutes}} \qquad \textbf{(4.7)}$$

Since angular speed (ω) is defined as the number of revolutions turned per minute (RPM), equation 4.7 can be expressed as

$$P = F(16)\omega\ \frac{\text{rev}}{\text{min}}\ (r)\text{ft}\ \frac{2\pi \text{ radians}}{\text{rev}}$$

$$P = F\omega 2\pi \text{ ft-lb/min} \qquad \textbf{(4.8)}$$

One horsepower is defined as

$$hp = 33000 \frac{\text{ft-lbs}}{\text{min}} = 550 \frac{\text{ft-lbs}}{\text{sec}} \qquad \textbf{(4.9)}$$

To relate torque to horsepower the following procedure is used:

Since, $T = Fr$ (From 4.3)

Combining equations 4.8 and 4.9, we will have

$$P = T\omega 2\pi \frac{\text{ft-lb}}{\text{min}} \times \frac{1\ \text{hp}}{33000\ \text{ft-lb/min}}$$

$$= \frac{T\omega 2\pi}{33000}\ \text{hp}$$

and $P = \dfrac{T\omega}{5250}$ hp

The rated torque delivered by a machine is calculated using

$$\boxed{T = \frac{5250\ \text{hp}}{\omega}} \qquad \textbf{(4.10)}$$

where T = torque lb-ft
ω = angular speed in RPM
hp = rated horsepower

The work done by an electric current may be the illumination of a room, the running of a motor for almost any kind of mechanical work, or the operation of a radio transmitter and receiver. The unit of electrical power is the *watt,* and is defined as the work done in one second by a steady current of one ampere flowing under a pressure of one volt. Mathematically this is

1 watt = 1 volt X 1 amp

or $\boxed{P = EI}$ **(4.11)**

By Ohm's Law, $E = IR$, and equation 4.11 can be expressed as

$$\boxed{P = EI = \frac{E^2}{R} = I^2R} \qquad \textbf{(4.12)}$$

Like mechanical power, electrical power can be expressed in units of horsepower:

$$\boxed{1\ \text{hp} = 746\ \text{watts}}$$

therefore,

1 watt = 1/746 hp

All energy conversion systems have losses to some degree. A pictorial illustration of the losses that may occur in a system comprising a motor and a load is shown in figure 4-8. On the right side is the mechanical power and on the left is the electrical power.

Electrical power is supplied to the motor, but because there are losses within the motor, the output power supplied is in mechanical form and is less than the input power. This can be expressed mathematically

$$P_{in} = P_{out} + \text{losses}$$

The losses that are encountered are the result of electrical and mechanical factors within the machine. These losses may be broken down into four main categories:

1. **Copper losses**
2. **Mechanical losses**
3. **No-load core losses**
4. **Stray load losses**

Copper losses are within the armature and field winding circuits. These are normally calculated as I^2R losses and are based on the DC resistance at 75°C. The brush contact loss at the commutator is usually considered to be 1.8 volts for carbon brushes.

Mechanical losses arise from friction and *windage* of the motor bearings, cooling fan blades and armature.

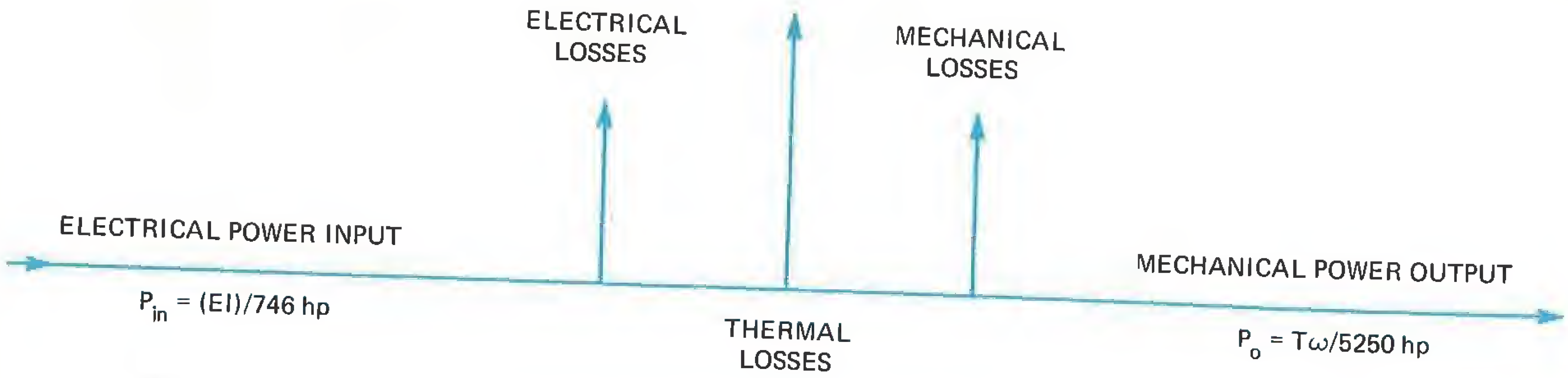


Fig. 4-8 Electrical Power Converted to Mechanical Power

The **no-load core losses** consist of *hysteresis* and *eddy-current* losses. The hysteresis losses occur when the *magnetic flux density* is changed. The eddy-current losses are caused by generation of currents in the rotor iron. Both eddy-current and hysteresis losses are reduced by fabricating the rotor from thin laminated sheets of low-loss magnetic material.

The **stray load losses** result from non-uniform current and magnetic flux distribution. Because of the difficulty in calculating, they are usually assumed to be about 1% of the output power for DC machines. All of these losses tend to increase with increased loading.

The efficiency of a system is defined as

$$\boxed{\% \text{ Eff} = \frac{\text{Power Out}}{\text{Power In}} \times 100}$$

From equation 4.12, the electrical input power can be defined as

$$P_{in} = I_a^2 R_a \text{ watts}$$

where R_a = armature resistance
I_a = armature current

The power output is

$$P_o = \frac{T\omega}{5250} \text{ hp}$$

Therefore, the efficiency would be given by

$$\% \text{ Eff} = \frac{\frac{T\omega}{5250} \text{hp} \cdot \frac{746 \text{ watts}}{1 \text{ hp}}}{I_a^2 R_a \text{ watts}} \times 100$$

$$\% \text{ Eff} = \frac{0.142\, T\omega}{I_a^2 R_a}$$

where T = torque in ft-lbs
ω = speed in RPM
R_a = armature resistance
I_a = armature current

When the armature starts to rotate, a voltage will be induced in the armature coils because of their cutting the magnetic field set up by the north and south poles. This emf is in the opposite direction of the impressed voltage (Lenz's Law) and is called the *counter emf.* The *cemf* is expressed by

$$\text{cemf} = \frac{2\phi C\omega}{10^8} = K\phi\omega$$

where ϕ = total flux
C = number of conductors in series
K = constant from equation 4.2

When the motor is operating at normal speed, the counter emf is slightly less than the impressed voltage. The cemf is lower than the applied voltage by the amount of the IR drop

in the armature which is expressed as

$$\text{cemf} = E - I_a R_a$$

where E = impressed voltage
I_a = armature current
R_a = effective armature resistance

The armature current is expressed as

$$I_a = \frac{E - \text{cemf}}{R_a} = \frac{E - K\phi\omega}{R_a} \quad \textbf{(4.14)}$$

The input power would therefore be

$$P = I_a^2 R_a = \frac{(E - \text{cemf})^2}{R_a} \text{ or}$$

$$(E - \text{cemf})\, I_a \quad \textbf{(4.15)}$$

not $P = EI$

When a load is applied to the shaft of a motor, the following results occur:

1. Motor speed goes down
2. As a result, the cemf goes down
3. As a result, the armature current goes up
4. And the power increases to the load.

When the load is reduced the reverse reactions occur:

1. Motor speed goes up
2. As a result, the cemf goes up
3. As a result, the armature current goes down
4. And the power decreases to the load.

From the previous paragraph it should be apparent that the speed varies as the load is changed. Speed regulation of a motor expresses the amount of variation between the speed of the motor with zero load and the speed with full load. This can be expressed as

$$\%\text{ regulation} = \frac{\omega_{NL} - \omega_{FL}}{\omega_{FL}} \times 100$$

where ω_{NL} = speed at no load, RPM
ω_{FL} = speed at full load, RPM

It is quite important that the proper motor be chosen for the mechanical load with which it is to be used. Most manufacturers of electric motors employ engineers in their field service organizations to assist in the selection of the proper size and type motor for given load requirements. When purchasing a large piece of equipment, it is well to consult with one or more of these groups; otherwise, a poorly selected motor could result in higher energy costs, inefficiency, poor service, overheating, breakdown, and other increased maintenance and operating costs.

Motors are rated in terms of their output capacity in shaft horsepower at rated speed, full-load current, and applied voltage. When operated under these nameplate conditions, the motor will not overheat. Temporary overloads are permissible; but if carried for long periods of time, the motor will overheat. Most motors are designed to tolerate a temperature rise of approximately 140° F with safety.

Motor Ratings:

a. Horsepower –
   Less than 1 hp – fractional hp motor
   More than 1 hp – integral hp motor

b. Voltage: + 1.5 to 1500 volts

c. Freq: 60 Hz, also 25, 40, 50, and 400 Hz.

d. Speed: RPM

e. Torque:

Integral motors are rated in pound-feet
Fractional motors are rated in ounce-inches, 192 oz-in = 1 lb-ft

f. Duty cycle: Time on/Time off

1. Continuous
2. Intermittent

g. Temperature

40 to 50° C above ambient temperature of 25°C — continuous
50 to 55°C above ambient temperature of 25°C — intermittent

h. Efficiency

i. Speed regulation

Two tests can be used to determine the losses in a motor — the *no-load* test, and the *load-test*. In this experiment the no-load test will be used.

No-Load Test

With the rated voltage applied to the motor at no load, i.e., no load attached, the input can be measured directly. Since there is no power output, the power consumed in the stator is in the form of *copper losses, core losses,* and the *friction* and *windage losses* in the rotor. All of the power supplied to the motor is considered a loss because the output power is zero.

$$P_o = P_{in} - P_L$$

or

$$P_{in} = P_L$$

From equation 4.15,

$$P_{in} = (E\text{-cemf})\ I_a$$

Therefore, with no load

$$P_L = (E\text{-cemf})\ I_a$$

The voltage E and current I_a can be measured by instruments in the lab. The cemf of the motor can be determined by turning the motor shaft at a fixed RPM and measuring the generated output voltage. The cemf of a motor is exactly the same as the output voltage of the same machine acting as a generator.

MATERIALS

2 DC motors, 28 volt, 0.7 amp, 7000 RPM

1 DC power supply, 0 — 30 volts

2 VOM meters

1 Stroboscope

1 Motor shaft coupling

1 Breadboard with legs

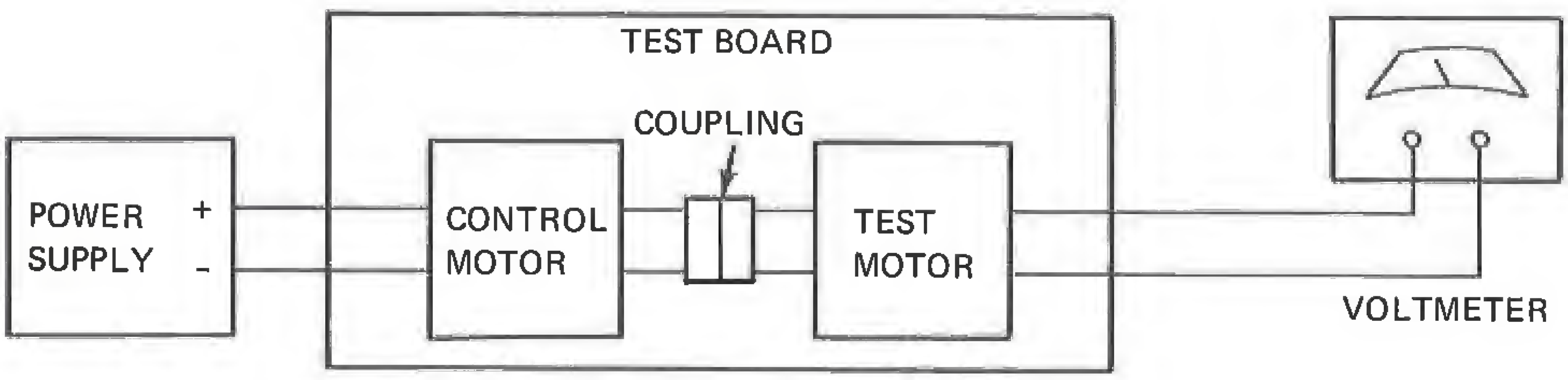


Fig. 4-9 Circuit to Obtain Cemf of Motor

PROCEDURE

1. Couple the two motors together as shown in figure 4-9. Mount the motors on the breadboard so that they will not move.
2. With zero RPM of the control motor, the output voltage of the test motor should be zero. Record this in figure 4-11.
3. Increase the voltage across the control motor until the RPM is 200. Record the voltage output of the test motor. (E_A)
4. Repeat step 3 for values of 400, 600, 800, 1000, 1500, 2000, 3000, 4000, 5000, and 6000 RPM. Do not allow the input voltage to the control motor to exceed the rated 28 volts.
5. Disconnect the circuit used and connect the test motor as shown in figure 4-10.

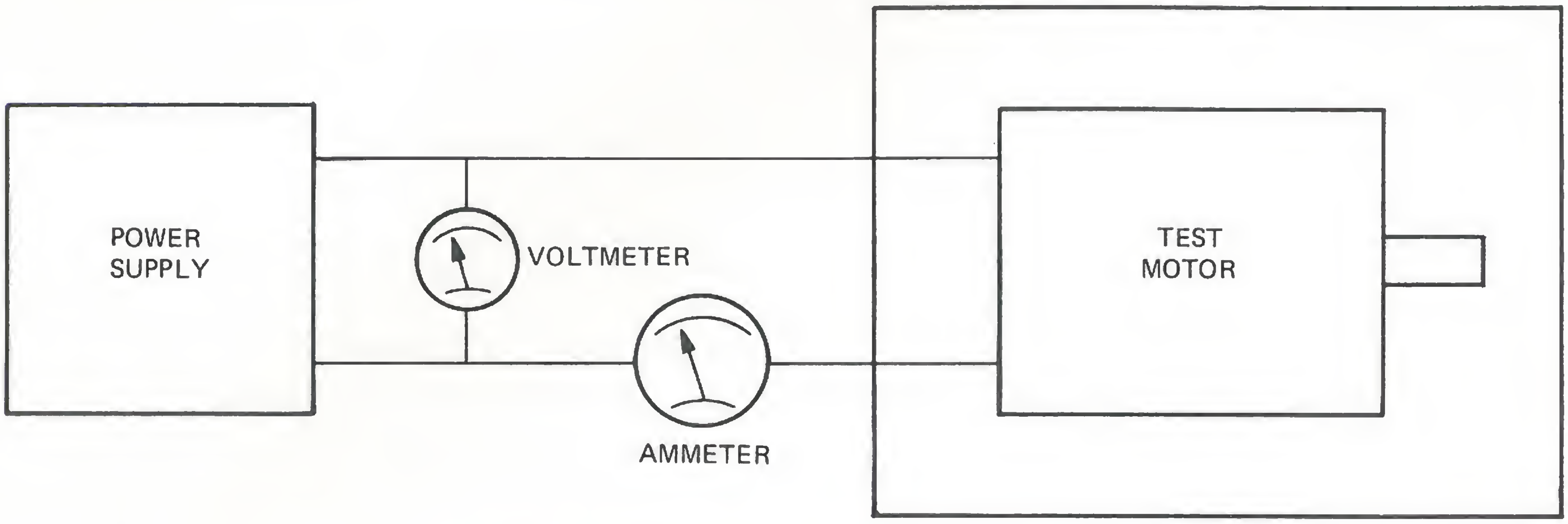


Fig. 4-10 Circuit for No-load Test

6. Increase the voltage to the test motor until the RPM of the motor is 200.
7. Record the corresponding current and supply voltage in figure 4-12.
8. Increase the voltage until the RPM is 400. Repeat step 7.
9. Repeat steps 7 and 8 for all values of RPM used in step 4.
10. Compute the difference in input voltage and cemf for all values of RPM.
11. Determine the power loss P_L for all values of RPM.

ANALYSIS GUIDE. Plot a graph of cemf versus RPM from figure 4-11. Also plot graphs of power loss versus RPM and P_L versus armature current from figure 4-12. What range of speed would be most suitable for this particular motor? Explain using the three graphs.

PROBLEMS

1. What is the percent efficiency of a one-half hp motor that uses 500 watts from the power source?

2. What is the percent efficiency of a 5-hp DC motor if it has the following losses: 525 watts in the iron core; 50 watts in the field copper; 175 watts in the armature copper; and 210 watts in windage and friction?
3. What is the rated full-load torque of a 2-hp, 2000-RPM motor?
4. What is the horsepower rating of a motor that delivers 4.2 oz-in of torque at 3000 RPM?

RPM	Cemf (volt. output)
0	0
500	
1000	
1500	
2000	
3000	
4000	
5000	
6000	

Fig. 4-11 Cemf of Motor Versus RPM

From	Experiment		Compute	Compute Power Loss
RPM	E_A	I_a	E_A – Cemf	$P = (E_A - \text{Cemf})\ I_a$
0	0	0	0	0
500				
1000				
1500				
2000				
3000				
4000				
5000				
6000				

Fig. 4-12 Power Loss Versus RPM

experiment 5 MOTOR LOAD TEST

INTRODUCTION. Modern applications of electric motors include such fields as industry, transportation, automation, electronics, business, and data processing. In this experiment the student will investigate how motors perform under various loading conditions.

DISCUSSION. Electromechanical devices which convert electrical energy into mechanical energy can be divided into two groups: direct current and alternating current. Each of these groups may also be subdivided into power devices and control devices. Because of the inherent characteristics, the DC group is better suited for control applications, whereas the AC group is better suited to large-scale energy conversion.

Before getting into the loading of a motor, the principles of operation and some of the more important characteristics of the more commonly used types of DC and AC motors will be discussed.

DC MOTORS

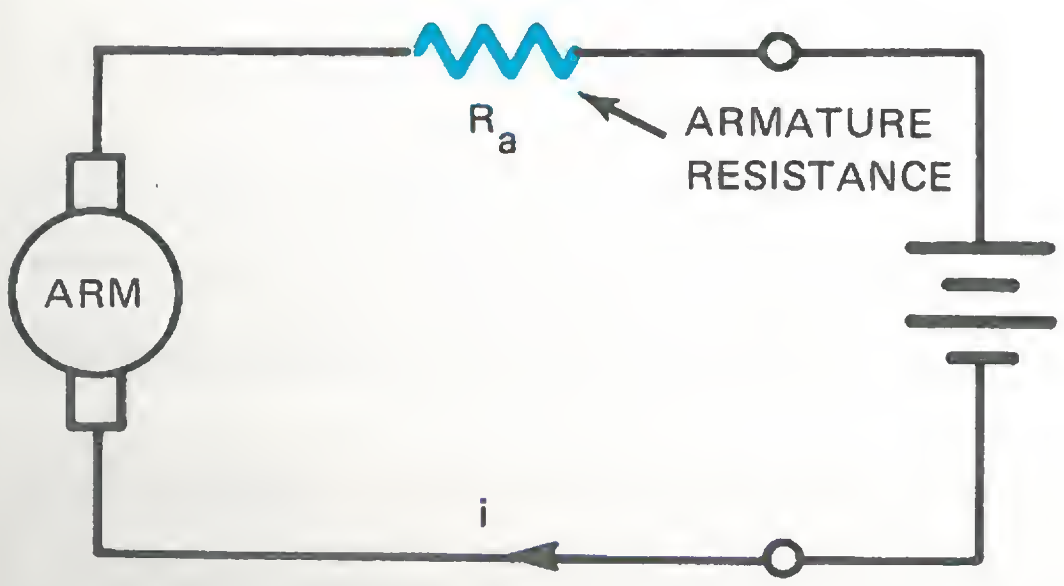
Direct current motors can be classified according to their type of field structure, either (1) *permanent magnet* or (2) *electromagnet.* The use of permanent magnets as field poles generally is limited to very small motors. Most medium-sized and large-sized motors use electromagnets for the field poles. The electromagnet motors are further classified in terms of the manner in which the field windings are connected in terms of the armature. These classifications include the *series, shunt,* and *compound* motors.

The construction of the three electromagnet motors is basically the same. For a particular horsepower and speed rating, the same basic *armature* might be used. The chief difference in construction is in the number of turns and the size of wire used in the field coil and the way the field coil is *excited.*

Permanent Magnet Motor

The permanent magnet motor utilizes a permanent magnet as its field. The armature rotates between the north and the south poles of the permanent magnet. When the armature cuts the magnetic field of the magnets, a *torque* is produced. The torque is dependent on the number of poles in the field, the number of conductors in the armature, flux produced per pole, and the armature current flowing.

The current reaches the armature by way of a *carbon brush* assembly and *commutator.*



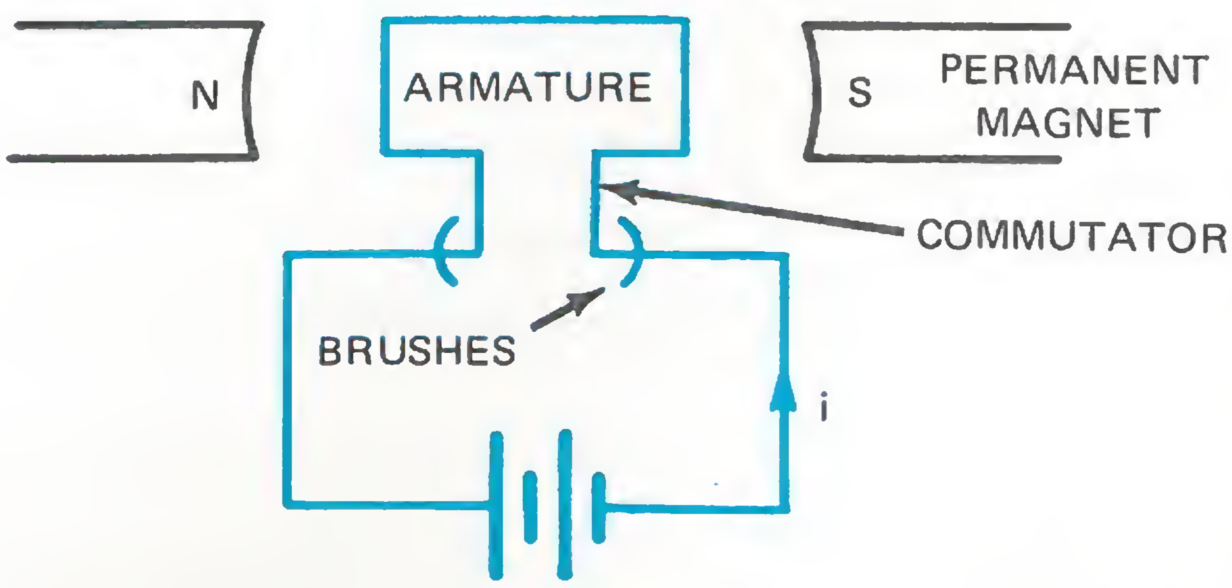


Fig. 5-1 Permanent Magnetic Motor

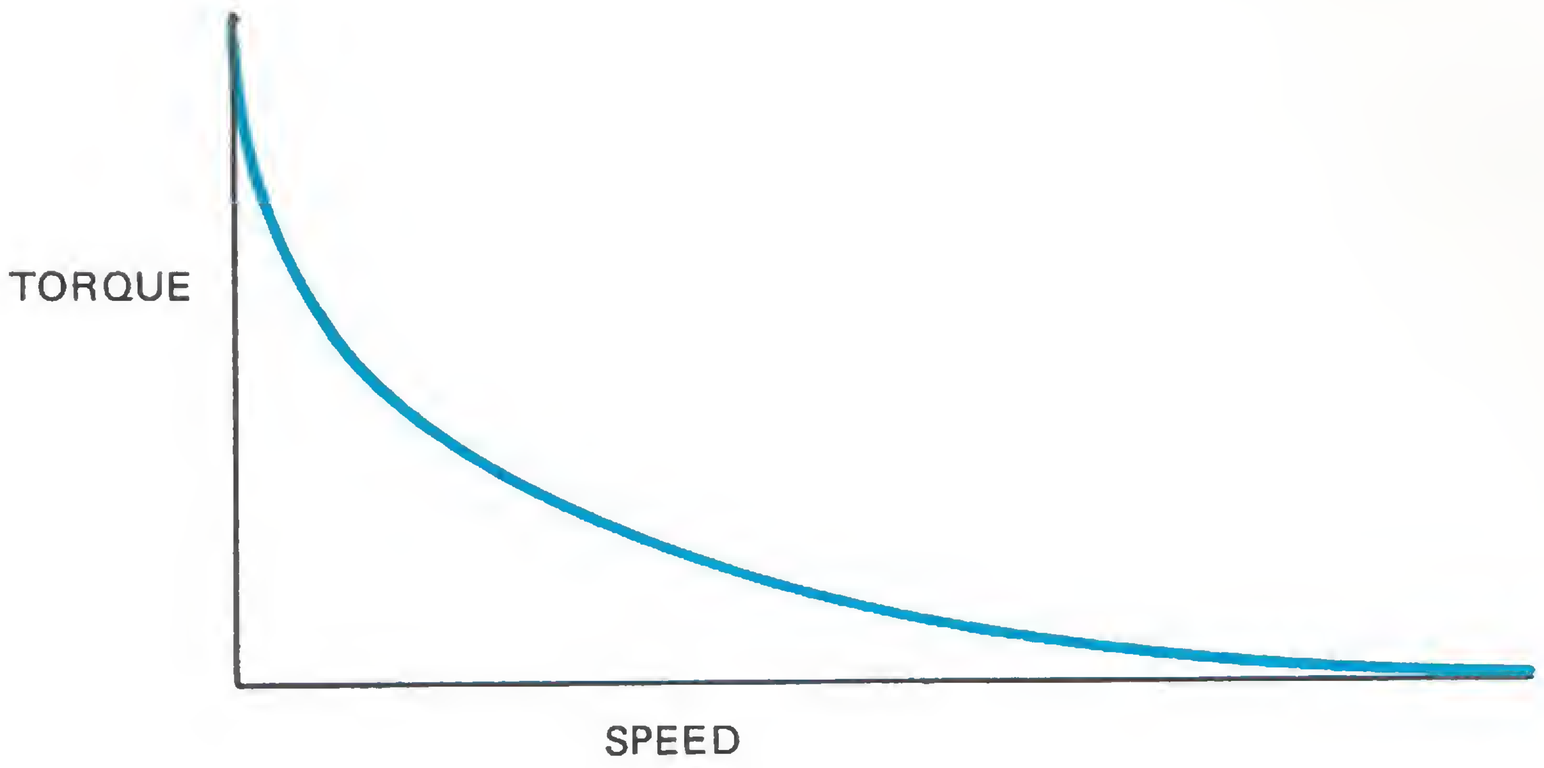


Fig. 5-2 Speed-Torque Characteristic Curve of Permanent Magnet Motor

This arrangement allows current to travel in the correct direction to keep the motor rotating in one direction. Figure 5-1 shows the schematic of the permanent magnet motor.

Figure 5-2 shows the speed-torque characteristics of the permanent magnet motor.

Since the torque is equal to:

$$T = K\phi_p I_a \tag{5.1}$$

where, T = torque lb-ft
ϕ_p = flux per pole
I_a = armature current
K = constant

the torque is almost solely dependent on the armature current. The value of K, which is dependent on the poles, and the flux per pole will not change due to the poles being permanent magnets. The only variable in equation 5.1 then would be the armature current. As the armature current goes up, the torque will increase. But according to figure 5-2, the speed will decrease to zero as the torque increases. For this reason, the motor has a poor *speed regulation.*

The smaller permanent magnet motors are produced as plain motors for direct connection to fans and blowers. Some have *centrifugal governors* for accurate speed regulation. Geared motors of this type are often used in positioning devices for remote tuning, trimming, antenna tilting, etc. Favorable characteristics are:

1. Ease of speed control by controlling armature current

2. Ease of reversibility by reversing the polarity of the input voltage

Unfavorable characteristics are:

3. Overloading may result in a loss of the field

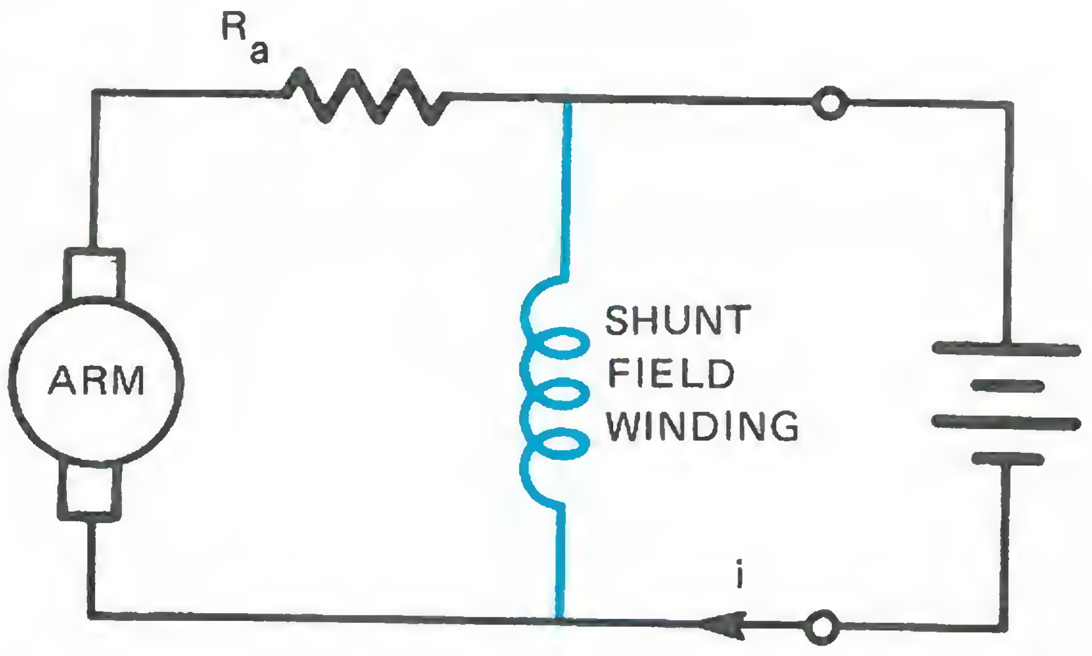
4. Poor speed regulation

Other uses of this type of motor are in:

1. Battery-operated toys.

2. Battery-operated clocks.

3. Tachometers in various forms of computers.



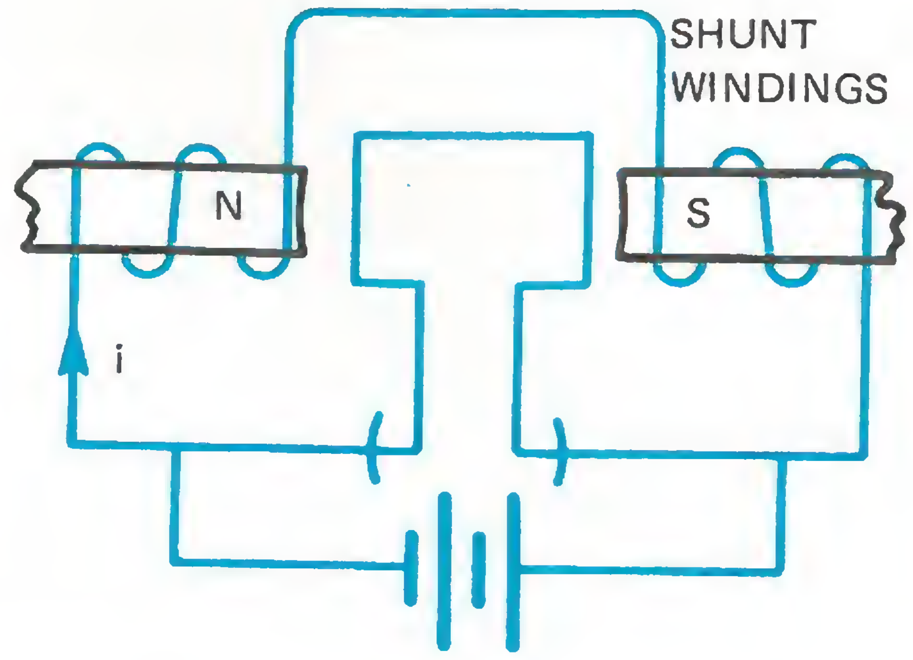


Fig. 5-3 Shunt Motor Schematic

Shunt Motor

A shunt motor has its field windings connected directly across the power source and since it is in parallel with the armature, it is considered to be *shunted* across the armature. Since the coils are connected directly across the power source, their resistance must be high in order to keep the value of field current low. The required number of ampere-turns is obtained by using a large number of turns of very small wire. Figure 5-3 shows the schematic of the shunt motor.

The torque for the shunt motor is related as in equation 5.1. As the field strength of a shunt motor is essentially constant, the torque will vary directly with the armature current. Also, because of the constant field strength, the variation of speed with varying load conditions is small. A shunt motor, therefore, has good speed regulation. The speed-torque characteristic curve and the armature current-torque curve are given in figure 5-4.

The shunt motor can provide a wide range of speed control by adding a variable resistance in its field circuit. This method is used when it is desirable to obtain speeds which are higher than rated speed.

A caution should be pointed out about the shunt motor. **If the field circuit of a shunt motor is broken, so that the flux approaches zero, the motor speed will increase to a dangerously high value.** The high speed may cause physical damage to the motor or its surroundings.

The direction of the rotating armature can be changed by interchanging either (1) the two leads of the field winding or (2) the two armature leads. Interchanging the leads to the motor reverses the current in both the armature and the field windings, and the motor does not change directions.

The characteristics of the shunt motor are:

1. High resistance field winding, large number of field turns.
2. Constant field strength.
3. Constant speed with varying loads, good regulation.
4. Small or moderate torque.

Some of the uses of the shunt motor are:

1. Motor generator units.
2. Machine tools.
3. Business machines.
4. Flexible shaft equipment.
5. Engraving machines.

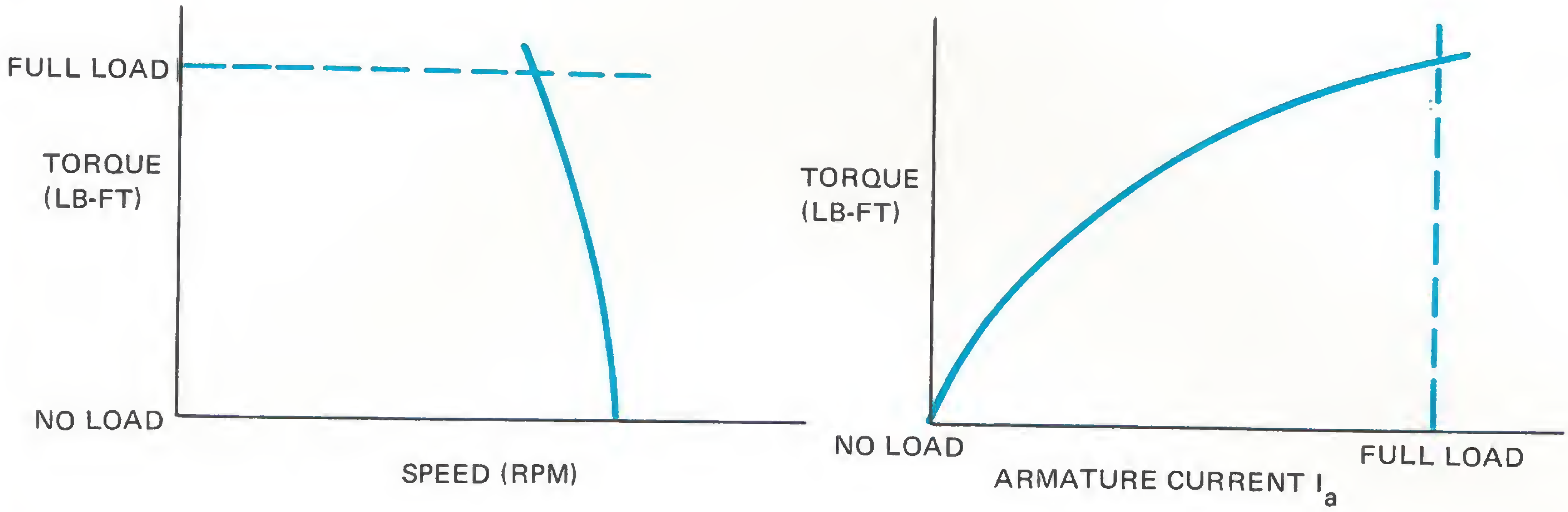


Fig. 5-4 Characteristic Curves of Shunt Motor

Series Motor

The series motor has its field windings connected in series with the armature. Unlike the shunt motor, the series field windings must carry the same current as the armature. For this reason the field winding is made of few turns of relatively large wire. A schematic of the series motor is shown in figure 5-5.

As the load on the series motor increases, the current in the armature and the field coils increases. Since the torque is proportional to both the armature current and the field strength, ϕ_p, the torque will vary as the square of the change in current. When the magnetic field reaches *saturation,* the torque will vary directly with the armature current. Because the field strength varies almost directly with the load, the variation of speed with load is very great, and the series motor is considered to have poor speed regulation. The speed-torque characteristic curve and the armature current-torque curve are given in figure 5-6.

Speed control is provided by inserting resistance into the armature circuit which, in turn, only reduces the speed.

If the load of a series motor comes loose from the shaft of the motor, the motor speed will increase to a very high value. For this reason, the load on a series motor should usually not be applied through pulleys and belts, but through gears or other positive drives.

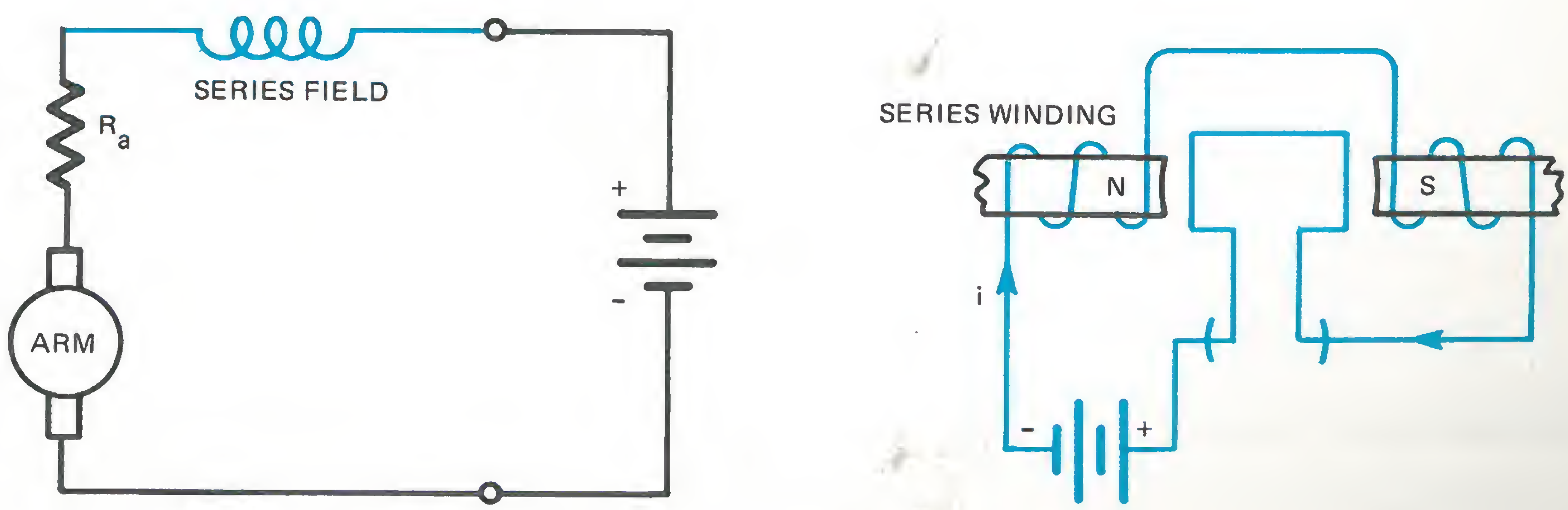
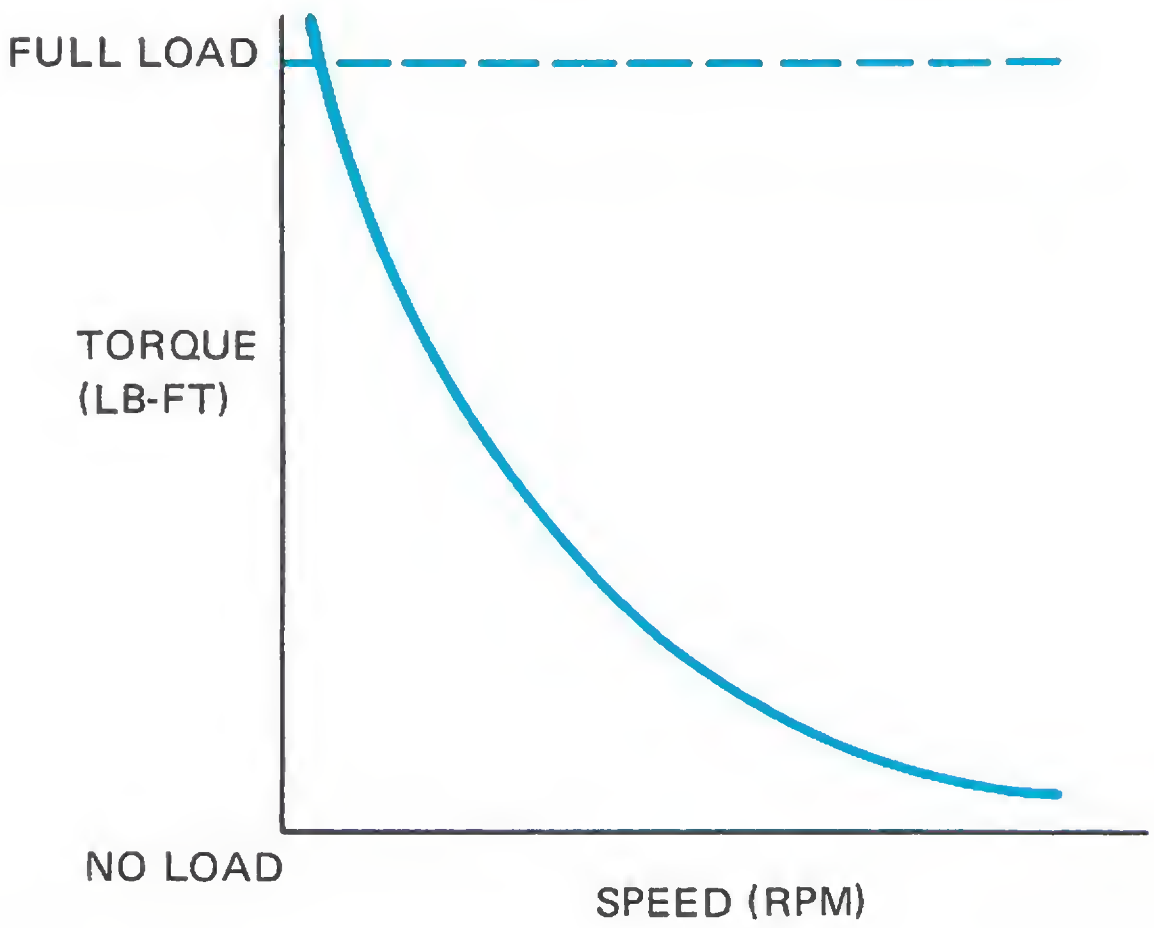


Fig. 5-5 Series Motor Schematic



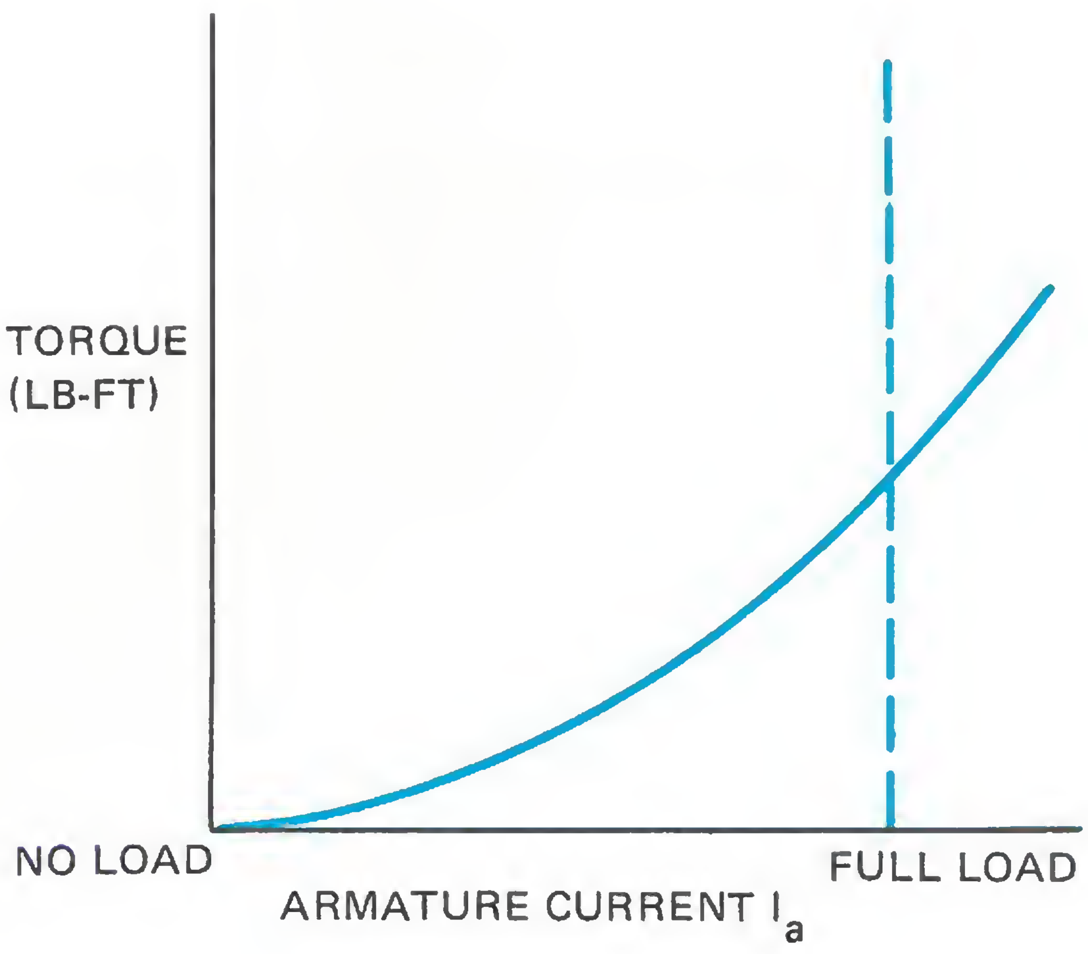


Fig. 5-6 Characteristic Curves of Series Motors

Reversing the direction of rotation of a series motor can be accomplished by either exchanging the two leads to the field winding or exchanging the two armature leads. Exchanging the input leads to the motor exchanges the current in both the armature and field windings and, hence, does not reverse the motor direction.

The series motor characteristics are:

1. Low resistance field windings, small number of field turns.
2. Field strength varies with armature current.
3. Varying speed with load, poor speed regulation.
4. Very high starting torque.

Some of the uses of the series motor are:

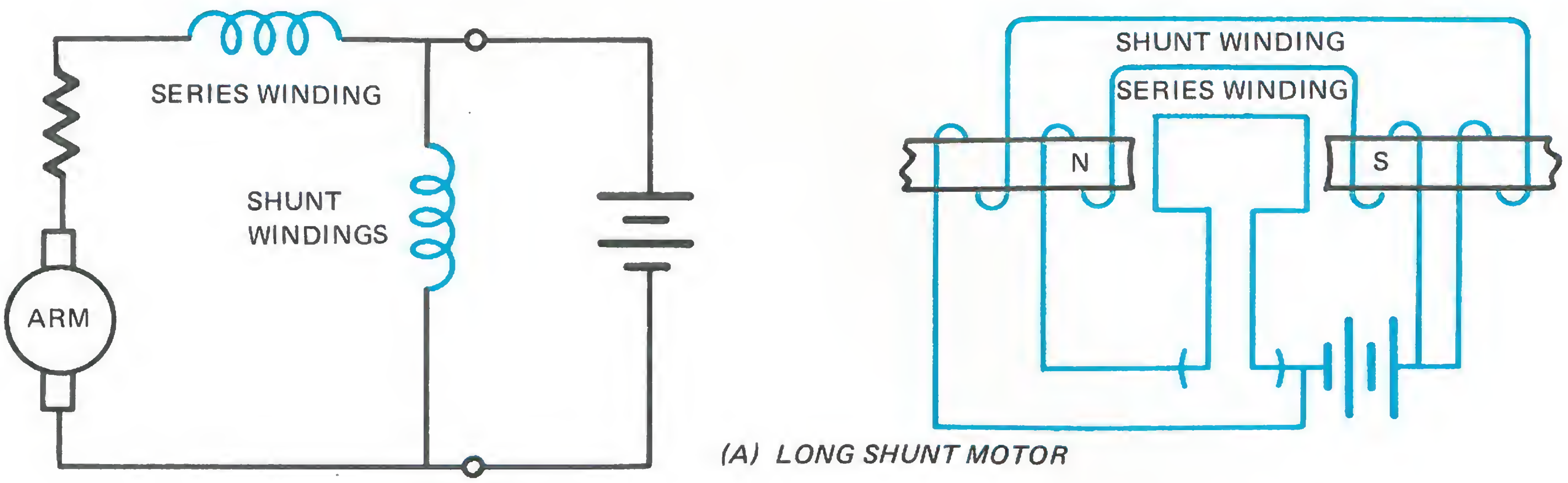
1. Hoists and cranes.
2. Conveyor systems.
3. Mixing machines.
4. Small hand tools.

Compound Motor

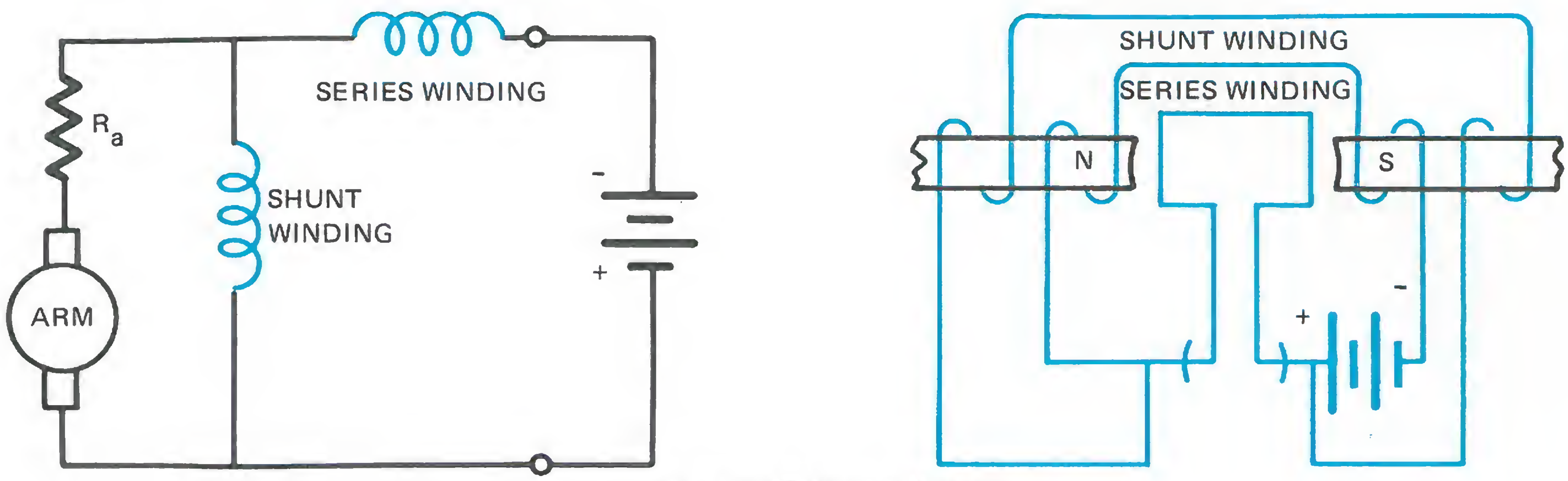
The compound motor has both a shunt field winding and a series field winding. When the shunt and the series field windings produce the same magnetic polarity at the poles of the motor, the motor is considered to be *cumulative compounded.* When the windings produce opposite polarities, a *differential compounded* motor is the result.

The motor can also be considered to be a *long shunt* or *short shunt* motor depending on the connection of the shunt winding. When the shunt receives the full input voltage it is considered to be a long shunt motor. The shunt winding is made of many turns of fine wire and has a high resistance. The series winding is made of few turns of large wire and has a low resistance to electron flow. Figure 5-7 gives the schematic of both the long and short shunt compound wound motors.

The torque of the compound motor lies between the shunt and series motor, and depends on the percentage of compounding and whether the connection is for cumulative or differential operation.



(A) LONG SHUNT MOTOR



(B) SHORT SHUNT MOTOR

Fig. 5-7 Compound Motor Connections

The speed regulation also depends on whether it is a cumulative or differential compounded motor. The differential motor can be made to have better speed regulation than the shunt motor. Figure 5-8 shows the characteristic curve for the compound motor.

Speed control can be obtained with a field rheostat for speeds higher than full rated speed, and with an armature resistance to provide speeds lower than full rated speed.

The loss of load and loss of field current characteristics are similar to those of the plain series and plain shunt motor respectively.

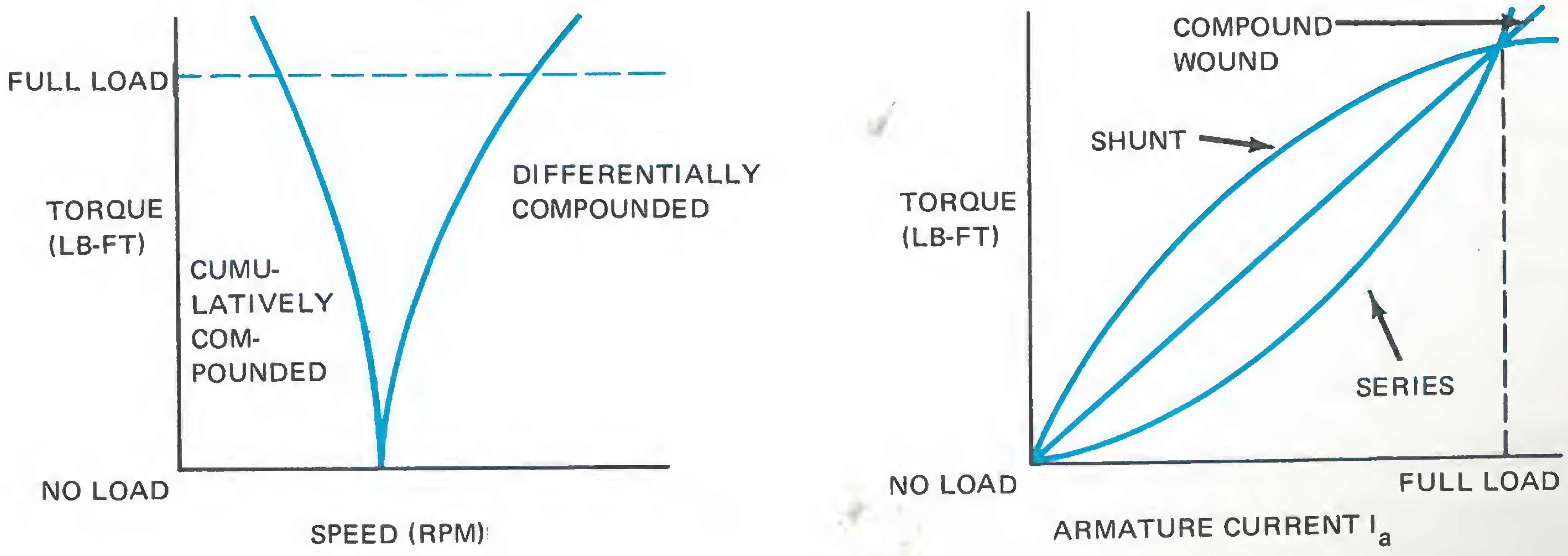


Fig. 5-8 Characteristic Curves of a Compound Motor

The direction of rotation of the rotor can be reversed by: (1) interchanging the two armature leads, or (2) interchanging both the two shunt field leads and the two series field leads. Reversing the current in only one field winding will change the motor from cumulative to differential, or vice versa, and can result in unsatisfactory motor operation.

The characteristics of the compound motor are:

1. Contains both series and shunt windings.
2. Characteristics are between those of a shunt and a series motor.
3. Wide range of torque and speed characteristics.
4. Adaptable to a wide range of applications because of the flexibility in design.
5. Cumulative compound motor produces a higher starting torque than the shunt motor.

AC MOTORS

Alternating-current motors are also made in a wide variety of types and are divided into a number of classifications. The major classifications are based on the power requirements, namely, (1) *polyphase* and (2) *single phase.* They are further classified in terms of the operating principles, such as (1) induction, (2) synchronous, (3) split phase, (4) shaded pole, (5) repulsion, (6) universal, (7) hysteresis, and (8) selsyn.

The basic operation of the AC motor requires (1) establishing a rotating magnetic field within the motor and (2) having the rotating magnetic field cut the conductors of its associated members so that a torque will be developed between the two members.

The rotating member of the AC motor is commonly known as a *rotor.* It consists of a number of conductors placed in slots located on the outside of an iron core which is mounted on the shaft of the motor. When AC power is supplied to the field windings, a rotating magnetic field is produced in the stationary member (known as the *stator*). The rotating magnetic field of the stator cuts the rotor conductors and induces an alternating voltage in the conductors. A high current will flow in these conductors setting up magnetic fields in the iron core of the rotor. The poles of the rotating field of the stator will exert a force on the poles of the rotor pulling the rotor around the rotating magnetic field of the stator.

Torque, power and work are terms that are often used with electric motors and other electromechanical devices. Torque is created by a rotating member, as in the case of a motor, and is defined as

$$\boxed{T = Fr}$$

where T = torque in lb-ft
F = force in lbs
r = radius in ft

Work is defined as the force needed to move a body times the distance the body is moved:

$$\boxed{W = Fd}$$

where W = work in ft-lbs
F = force in lbs
d = distance in ft

Power is defined as the rate of doing work and can be expressed as

$$\boxed{P = \frac{W}{t} = \frac{Fd}{t}}$$

where P = power in ft-lbs/min or ft-lbs/sec
W = work in ft-lbs
t = time in minutes or seconds

Power can be expressed in any units which indicate the work done and the time it takes to do the work. The customary units of power are the *horsepower* and the *watt*. Work is done at the rate of one horsepower when 33000 ft-lbs of work are done in one minute. Therefore

$$\text{Horsepower} = \frac{\text{ft-lbs in one minute}}{33000}$$

or $$\text{Horsepower} = \frac{\text{ft-lbs in one second}}{550}$$

The watt is the electrical unit of power. It is the product of the electric pressure in volts, the current in amperes which it is producing, and the power factor of the circuit.

Watts = volts X amps X power factor

The relationship between horsepower and watt is

1 hp = 746 watts

$$1\ \text{kilowatt} = 1000\ \text{watts} = \frac{1000}{746}\ \text{hp} \approx 1\text{-}1/3\ \text{hp}$$

Several methods are available to measure the power output of a motor. A common one makes use of a *dynamometer,* which may be merely an electric generator coupled to the motor under test. The generator can be loaded to absorb all the power produced by the motor. The electrical power is measured by an appropriate meter, which may be calibrated in either watts or horsepower.

The *Prony brake* provides a purely mechanical means for measuring power output. This device consists of a belt held under tension by two spring balances. The belt wraps around a drum on the shaft of the motor under test as shown in figure 5-9. As the motor turns, the drum exerts a frictional force on the belt that causes the tensions on the ends of the belt to differ. The magnitude, F, of the difference between the tensions is equal to the force exerted on the drum.

If the radius of the drum is r, the rotating drum does the work,

$$W = Fd = F(2\pi r)\ (\text{no. of revolutions})$$

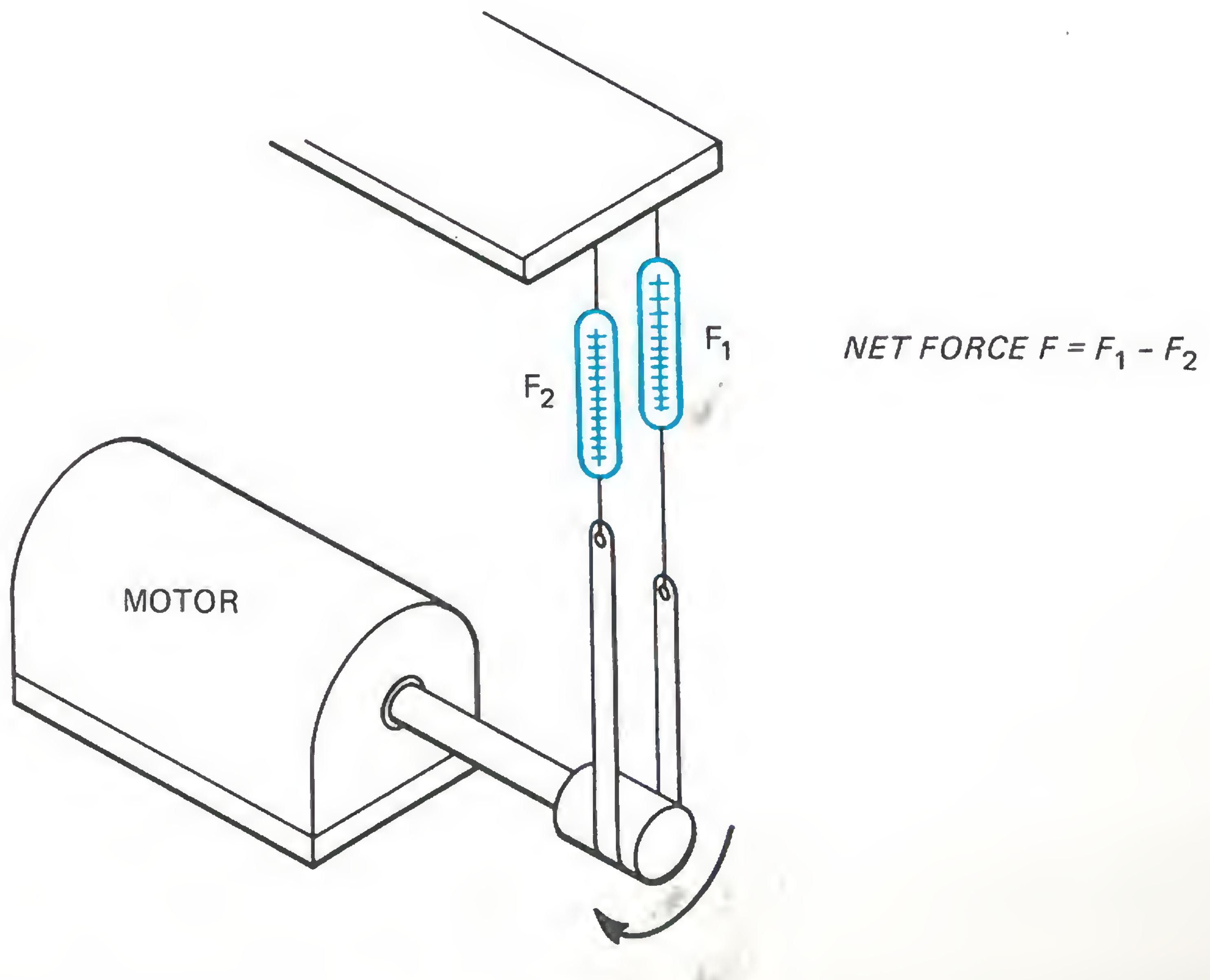


Fig. 5-9 The Prony Brake

Since the power is the work done per unit time, the power developed by the motor is therefore the work done per revolution multiplied by the number of revolutions per unit time. If the revolutions are in RPM, the power expressed in horsepower is equal to

$$\boxed{P = \frac{F 2\pi r \times \omega}{33000} \text{hp} = \frac{T\omega}{5250} \text{hp}} \tag{5.3}$$

The power obtained in this way is usually called *brake horsepower.*

The Prony brake makes use of applied *friction* (opposition) to produce the load torque. The torque has to overcome the opposition in order to do effective work.

The difference in the input power to the motor and the output power of the rotating shaft is known as the *power loss.* The power loss can be determined by the following formula

$$P_L = \frac{(E - \text{cemf})}{746} I_a - \frac{(F 2\pi r \times \omega)}{33000}$$

where P_L = power loss in horsepower
E = impressed voltage in volts
cemf = counter emf of motor in volts
I_a = armature current in amperes
F = resultant force of Prony brake $F_1 - F_2$ in lbs
r = radius of pulley or drum
ω = speed of motor shaft in RPM

The power loss is the result of the electrical losses due to the brushes, copper losses in the field and armature, mechanical losses due to friction of the moving parts of the motor, core losses, and stray losses. All of these effects are considered to be the real opposition of the motor. The friction between the drum and the belt of the Prony brake will give off energy in the form of heat. This energy is the load energy and must be dissipated by the Prony brake.

Every device which transforms energy from one system to another loses some energy in the process. Efficiency is the expression used to indicate what portion of the energy received by a device can be given out by it. Although efficiency may not strictly be considered a motor rating, it is of importance to the user in that it affects the cost of operating the motor. The efficiency of motors varies greatly with the size of the motor. Typical values are: 1/4 hp = 62%; 1 hp = 75%; 50 hp = 90%; 5000 hp = 97%. The efficiency of a motor can be calculated by

$$\text{percent efficiency} = \frac{\text{output}}{\text{input}} \times 100$$

or

$$\text{percent efficiency} = \frac{\text{input} - \text{losses}}{\text{input}} \times 100$$

In this experiment the cemf of the motor will not be measured. Instead, the I^2R power will be used as an approximation of the input power.

MATERIALS

1 Dynamometer

1 Series motor or DC motor

1 DC power supply with voltage and current meters

Appropriate couplings and motor mounts as needed

5 Sheets graph paper, 10 X 10 division per cm

PROCEDURE

1. Connect the motor to the dynamometer with the appropriate couplings and motor mounts. It is very important that all fittings are tight and that the shafts are aligned correctly.
2. Connect the DC power supply to the motor.
3. As voltage is applied to the motor, the load on the motor must be increased so that the motor will not over speed.
4. Increase the voltage and the load slowly until about 1/2 the rated voltage is across the motor and the RPM is about 2200.
5. Record the RPM, the force, the input voltage and the input current in the data table, figure 5-10.
6. Increase the load on the motor until the RPM decreases to about 200 RPM.
7. Record the same quantities in the data table.
8. Repeat steps 6 and 7 for several speed values until the motor stalls.
9. Turn off the supply voltage and decrease the load.
10. After the motor and dynamometer cool down, repeat step 4 but increase the voltage about 10 percent.
11. Rerun the experiment with this value of input voltage.
12. Calculate the torque applied by using equation 5.2. The radius arm will have to be measured in feet.
13. Calculate the power in and the power out for each load applied using the formulas given in the data table.
14. Calculate the efficiency for each load.
15. Measure the DC resistance of the motor ______________________ Ω.

ANALYSIS GUIDE. Using the data obtained, plot graphs of the following characteristics for both sets of data:

Torque versus Speed.

Current versus Torque.

Power in versus Power out in watts.

Current versus Power out in watts.

Torque versus Efficiency.

PROBLEMS

1. What ratio does the efficiency of a motor represent? How does the efficiency of a motor affect its operating cost?
2. How much torque is delivered by a 1/50-hp, 4000-RPM motor? How much force is developed at the surface of the rotating member if its diameter is 1-1/2 inches?
3. What is the efficiency of a 1/45-hp, 1600-RPM motor that takes 23.4 watts from the power source?

Volts	Force	Torque	Speed	Current	$P_{in} = I^2R$	$P_o = \frac{T\omega}{5250}$	P_o in watts	Eff.
50								
50								
50								
50								
50								
50								
50								
60								
60								
60								
60								
60								
60								
60								

Fig. 5-10 Characteristics of a DC Motor Data Table

experiment 6 TRANSFORMER LOSSES

INTRODUCTION. The *transformer* is a widely used piece of equipment in this modern age of technology. In this experiment we will examine some of the characteristics of the transformer and how loading affects these characteristics.

DISCUSSION. An important reason for the greater use of alternating current over direct current is the ease with which the voltage can be raised and lowered by use of transformers. Because of transformers, power can be generated in large quantities at the source of energy such as a *hydro-electric station* or a *power plant.* The generated voltage can then be raised to transmission-line values as high as 635,000 volts and can be transmitted to cities several hundred miles from the generating station. Upon entering the city, the voltage is reduced in a transformer substation to a reasonable level for distribution throughout the city. It is further stepped down by additional transformers for supplying consumer power.

Electromagnetic induction is the basic principle behind the operation of a transformer. Figure 6-1 shows a fundamental transformer consisting of a core of iron and two windings. The core provides a path for the *magnetic field* and is generally made of iron, steel or some other iron alloy, or it can have air as the core. The *primary winding* is the winding that receives the energy from the source and the *secondary* is the winding that delivers the energy to the load.

When the primary is connected to a source of alternating emf, an alternating current flows in that winding. The alternating current causes a continually changing magnitude and alternating polarity in the magnetic field that is set up in the core of the transformer. The alternating magnetic field is therefore, continually expanding and contracting. The variation of the magnetic field, ϕ, is the same anywhere in the core because the magnetic circuit is a closed path. The expanding and contracting magnetic lines will, therefore, cut conductors placed anywhere on the core, and according to Faraday's Law, an induced emf will be set up in the conductors. The generation of an emf in one winding by a changing current in another winding is known as *mutual induction.*

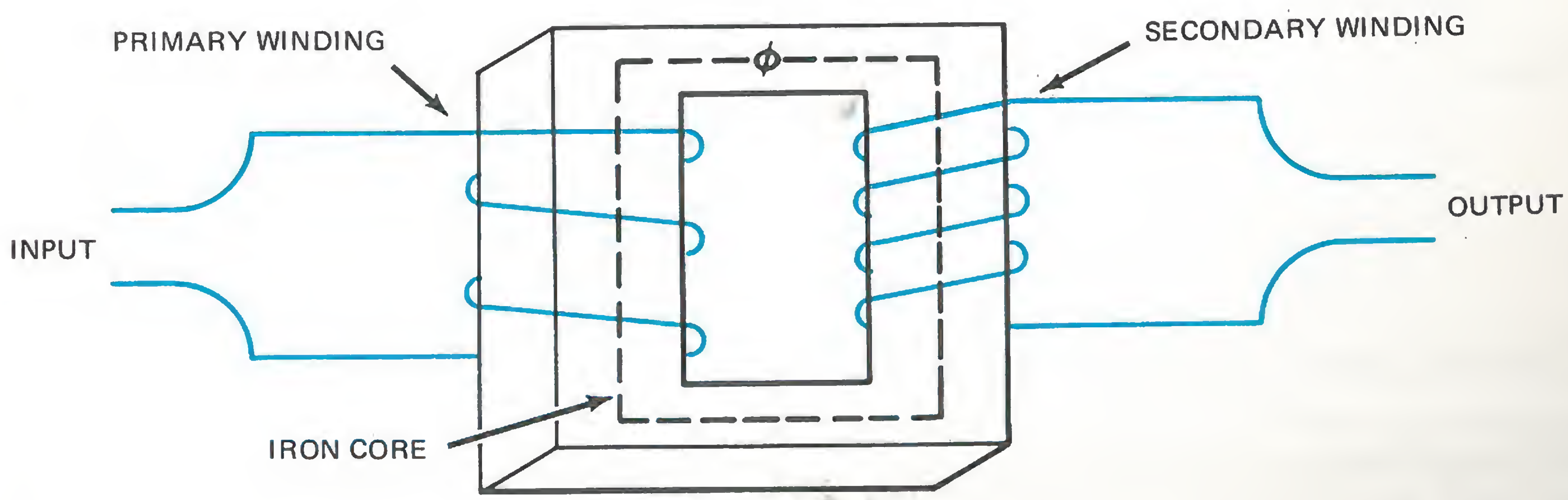


Fig. 6-1 A Fundamental Transformer

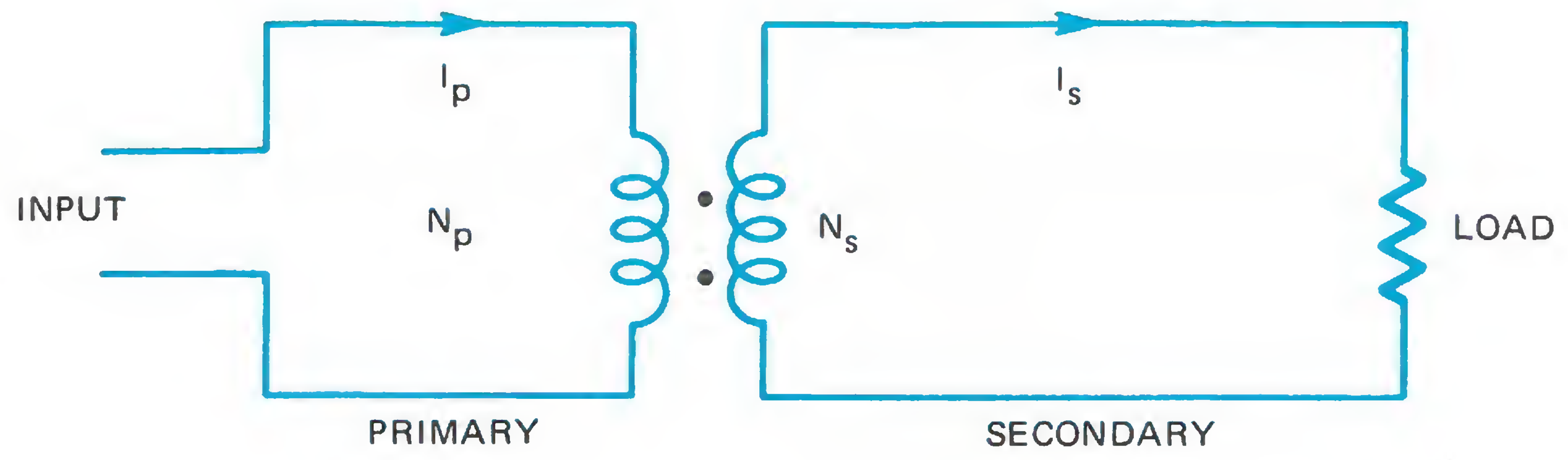


Fig. 6-2 Transformer With Load Applied To Secondary

In an ideal transformer, with sinusoidal input, all of the flux that is produced in the primary windings will *link* the secondary winding. Therefore, an emf will be induced in the secondary winding given by

$$E_s = 4.44\ fN_s\phi_m \qquad (6.1)$$

where E_s = secondary voltage
f = frequency of primary voltage
N_s = turns on the secondary
ϕ_m = peak value of the flux in webers

Because the same flux cuts each conductor on the core, the induced emf per turn will be the same. Therefore, the voltage of each winding will be proportional to the number of turns; that is

$$\boxed{\frac{E_p}{E_s} = \frac{N_p}{N_s} = a} \qquad (6.2)$$

where E_s = secondary voltage
E_p = primary voltage
N_p = primary turns
N_s = secondary turns
a = transformation ratio

The ratio given in equation 6.2 is known as the *transformation ratio* which is represented by a small letter a. From this equation it can be seen that the secondary voltage can be raised or lowered by using the proper ratio of turns.

If a load impedance is added to the secondary winding of the transformer circuit in figure 6-1, the emf induced in the secondary winding by the primary flux will cause current to flow in the secondary circuit. This current will cause an emf of N_sI_s ampere-turns to appear across the secondary. The power consumed by the load must be supplied by the source, hence the primary load must vary in the same manner as the secondary. Figure 6-2 gives a schematic of a transformer with a load applied to the secondary.

Figure 6-2 shows that there is no electrical connection between the primary and secondary windings. The power consumed by the load is transferred from the primary winding to the secondary winding by means of the magnetic flux.

The *efficiency* of the transformer is very high, often above 90 percent, so the power output must be very nearly equal to the power input. Under this condition, the currents vary inversely with the voltage. In other words

$$P_p = P_s \qquad (6.3)$$

which equals

$$E_p I_p = E_s I_s$$

which, in turn, yields the following:

$$\boxed{\frac{E_p}{E_s} = \frac{I_s}{I_p}} \qquad (6.4)$$

where P_p = power of the primary
P_s = power of the secondary
I_p = current in primary
I_s = current in secondary

Equation 6.4 shows that as the voltage is stepped up, the current is stepped down. This is one advantage which is utilized in transmitting power.

Since power is equal to current times voltage, the current will be small in the power lines with a high voltage. Since the power is dissipated in the form of heat at the rate of I^2R, the smaller the current, the less the power loss in the transmission line.

Since the power of the primary equals the power of the secondary, equation 6.3 can also be written as

$$I_p^2 R_p = I_s^2 R_s$$

or

$$\frac{R_p}{R_s} = \frac{I_s^2}{I_p^2}$$

and

$$\frac{I_s}{I_p} = \sqrt{\frac{R_p}{R_s}} \qquad (6.5)$$

where R_p = reflected resistance into primary
R_s = resistance across secondary

When the load is inductive, capacitive, resistive or a combination of these three, the impedance, Z, is used in equation 6.5. This gives the equation

$$\frac{I_s}{I_p} = \sqrt{\frac{Z_p}{Z_s}} \qquad (6.6)$$

where Z_p = reflected impedance of the primary
Z_s = impedance across secondary

In a good transformer the impedance of the secondary winding will be small compared with the load impedance. This results in the equation

$$\boxed{Z_p \approx \left(\frac{N_p}{N_s}\right)^2 Z_L} \qquad (6.7)$$

where Z_p is called the *reflected impedance* of the primary.

Because of the relationship shown in equation 6.7, transformers are used as a means of transforming a given load impedance into a different value for maximum power transfer. This principle is used in *impedance matching* applications where maximum power transfer is desired.

Combining equations 6.2, 6.4, and 6.6 will give a useful set of ratios that can be used when working with transformers

$$a = \frac{E_p}{E_s} = \frac{i_s}{i_p} = \frac{N_p}{N_s} = \sqrt{\frac{Z_p}{Z_s}} \qquad (6.8)$$

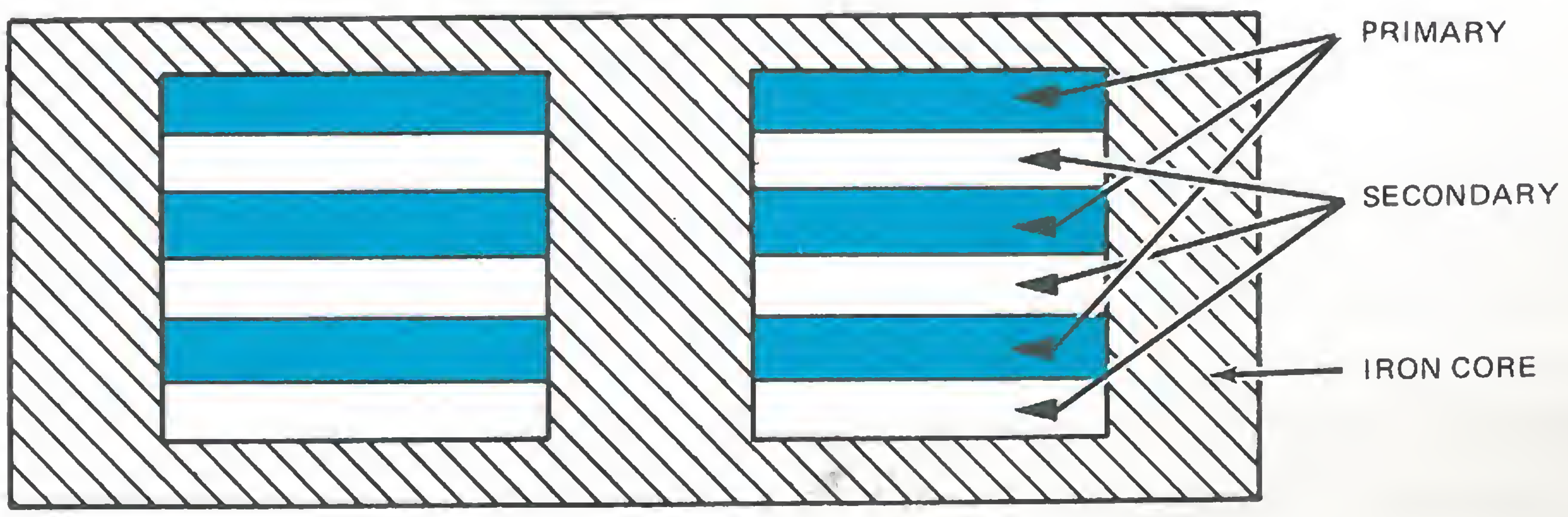


Fig. 6-3 Shell-Type Transformer Cross-Section

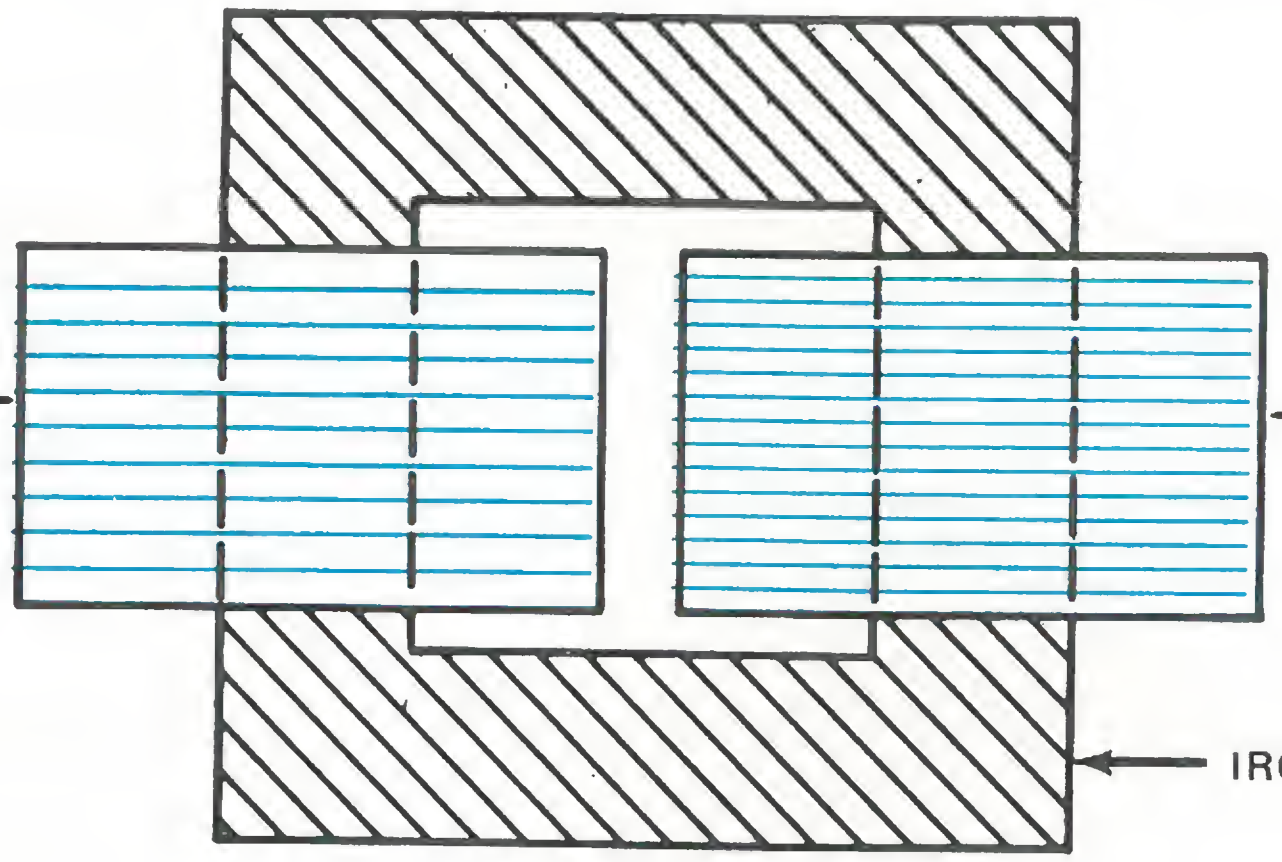


Fig. 6-4 Core-Type Transformer

There are two basic types of transformer construction, the *core type* and the *shell type.* The shell-type transformer is used when insulation is not a major problem, and it is desired that a high percentage of the flux produced in the primary link the turns of the secondary. Insulated coils of the primary and secondary windings are placed alternately about a central limb of an iron core, which encloses both windings. The core-type transformer can be either an *air-core* or an iron-core type. In the iron-core type, the primary and secondary windings are wound around an iron core as shown in figure 6-4.

The core consists of a high quality specially treated steel. The area between the core and the coil is wrapped with an insulator (a common one is paper). The wire has a special type of varnish on it to keep the wires from short circuiting.

The air-core transformer is similar to the iron-core type except that the core of the transformer consists only of air. The coils are wrapped around some type of nonmagnetic material. A simple core could be the cardboard tube found in the center of a paper towel roll. Figure 6-5 shows an air-core transformer.

The air-core transformer has very little mutual coupling between coils of wire because the *reluctance* of air is significantly greater than the reluctance of a magnetic material. As in electrical circuits, the higher

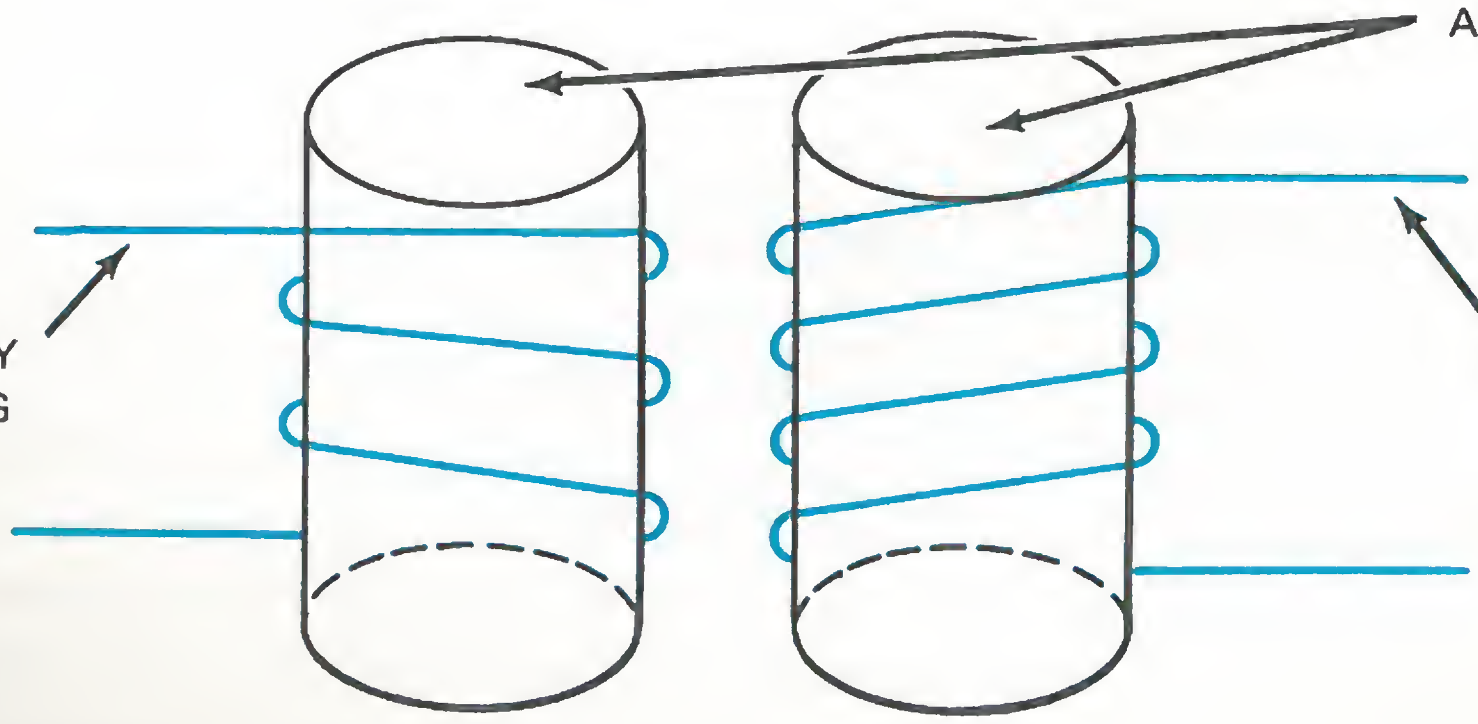


Fig. 6-5 Air-Core Transformer

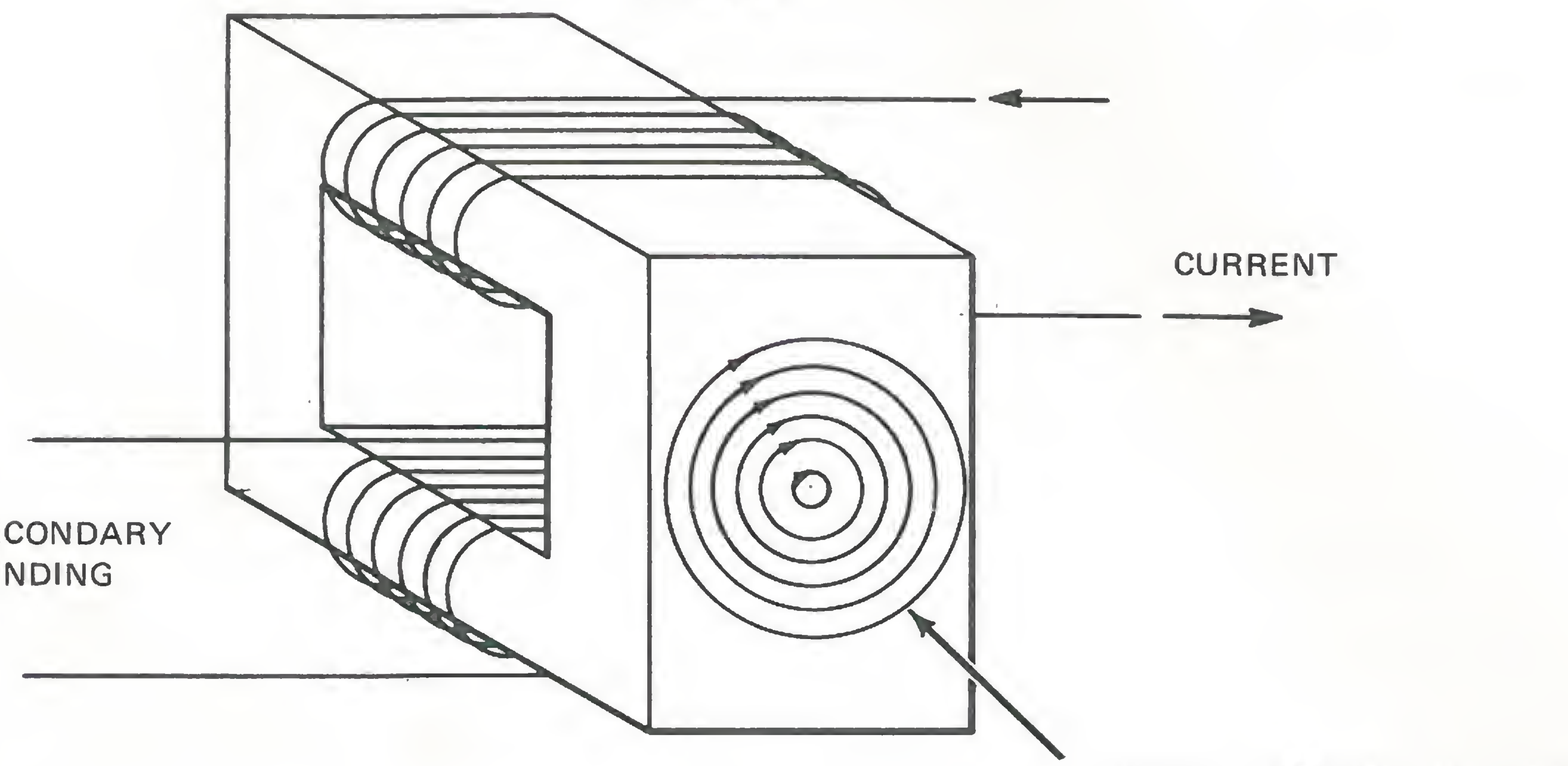


Fig. 6-6 Path Of Eddy Currents In a Solid Iron Core

the *reluctance* (resistance), the greater will be the opposition to the circulating magnetic flux. Because of this, the air core transformer has limited use; it is found mainly in high frequency applications and radio tuning circuits.

There are three main types of losses encountered in the transformer:

(1) *eddy currents,*

(2) *hysteresis,*

(3) I^2R *losses* (copper losses).

When a transformer is energized the changing primary field induces a current into any secondary which can provide a closed path. The transformer core itself can provide one of the possible paths. Consequently circulating currents called *eddy currents* flow inside the core material. Figure 6-6 illustrates such a condition. The eddy currents cause power to be dissipated within the core raising its temperature and reducing its efficiency.

Eddy currents can be reduced (but not eliminated) by using many thin sheets of core material rather than a single piece. When this is done the sheets or *laminations* must be electrically insulated from each other so that eddy currents will not flow from one to another. Insulation is achieved by using varnish and natural oxides between the laminations.

The eddy current effect depends on the rate of change of the primary field and therefore on the excitation frequency. Transformers that are used at high frequencies employ powdered iron or air cores to combat eddy current establishment.

Both powdered iron and laminated cores suppress eddy currents by cutting down the length of the paths available to the current. Consequently the thinner the laminations or the smaller the powder particles used, the better the eddy current situation. Figure 6-7 shows how a laminated core is constructed from the thin sheets of iron.

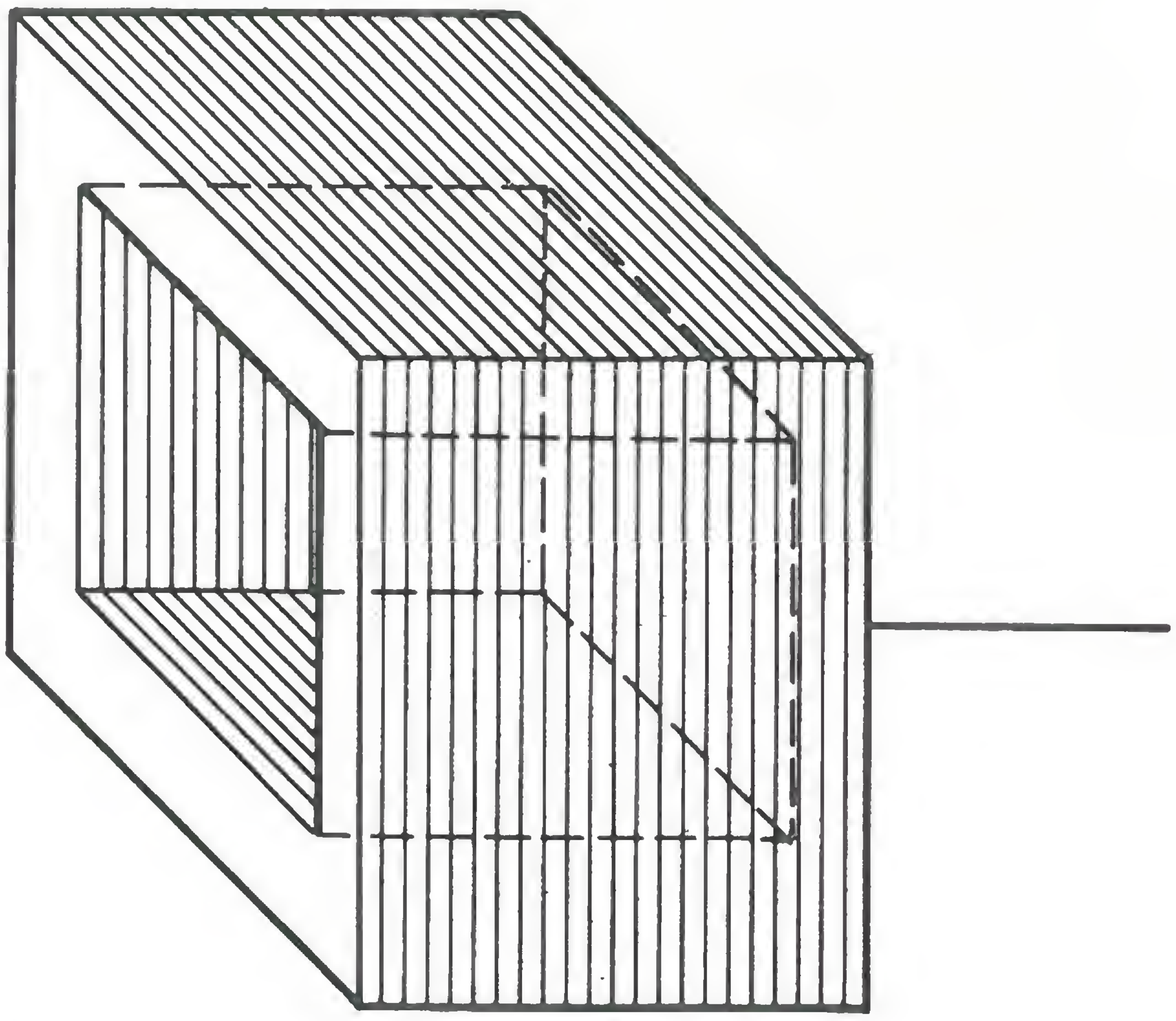


Fig. 6-7 Laminated Core Transformer

There is another transformer effect that depends on the changing primary field. It is called *hysteresis loss* or sometimes just *hysteresis.* The hysteresis effect arises out of the fact that it takes some energy to magnetize the core iron. Then when the field reverses, this magnetizing work must be done all over again. As a result, we must do this work over during every alternation of the input cycle.

Hysteresis loss like eddy currents is more serious at higher frequencies. But, unlike eddy currents hysteresis loss is not reduced by laminating or powdering the core. All we can do is try to select iron which can be easily magnetized and remagnetized.

In addition to hysteresis loss and eddy current loss we also have power loss in the transformer windings. This kind of loss is called *copper* loss. It is simply the power loss due to current flow in the copper wire. Copper losses can be evaluated using

$$P = I^2 R$$

provided that the value of R we use is the DC resistance of the coil. Copper losses are, of course, present in every active winding of a transformer.

The total loss in a transformer will be the sum of the hysteresis loss, the eddy current loss and the copper losses of all of the active windings. The copper losses can be *approximated* by measuring the DC resistance of each winding. Then when we connect it in a circuit the current can be measured. Then the copper loss is approximately equal to the sum of the individual winding currents squared times the resistance of the winding, that is

$$P_L = P_C + I_1^2 R_1 + I_2^2 R_2 + \cdots + I_n^2 R_n$$

where P_L = Total losses

P_C = Core losses

I_1 = Current in winding No. 1

R_1 = Resistance of winding No. 1

etc.

Core losses can be approximated by connecting *only* the primary winding. Then the input power is the sum of the primary copper

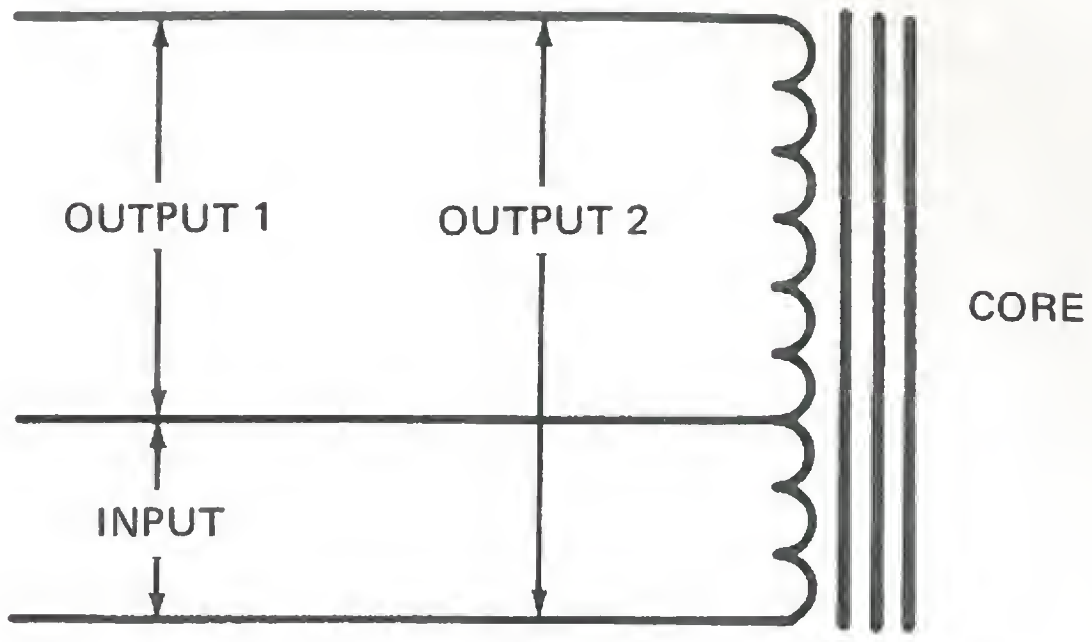


Fig. 6-8 Schematic Of Autotransformer

loss and the core loss. So if we know the primary core loss and the input power, we can get the total core losses.

However, this total core loss is the combined hysteresis and eddy current loss. There isn't a simple way that we can evaluate these core losses individually.

A transformer can be built using only one winding. Figure 6-8 shows such a case. This type of construction is called an autotransformer and is widely used. An autotransformer always has an electrically connected primary and secondary. We say that the autotransformer is not electrically *isolated.*

To get isolation of one circuit from another, the autotransformer shown in figure 6-8 could be changed to a common transformer with a tapped secondary as shown in figure 6-9.

It must be remembered that transformers can be used to step up or step down the input power. However, with the power losses described above, the output power is always lower than the input power. This is not uncommon, however, for all devices which change or transfer energy from one form into another form lose some of the energy in the process.

The efficiency of the transformer is found in much the same way as the efficiency of a motor,

$$\text{efficiency} = \frac{\text{output}}{\text{input}}$$

$$\%\ \text{efficiency} = \frac{\text{output}}{\text{input}} \times 100 = \frac{\text{input-losses}}{\text{input}} \times 100$$

To determine the amount of power losses in a transformer the following two circuits can be used.

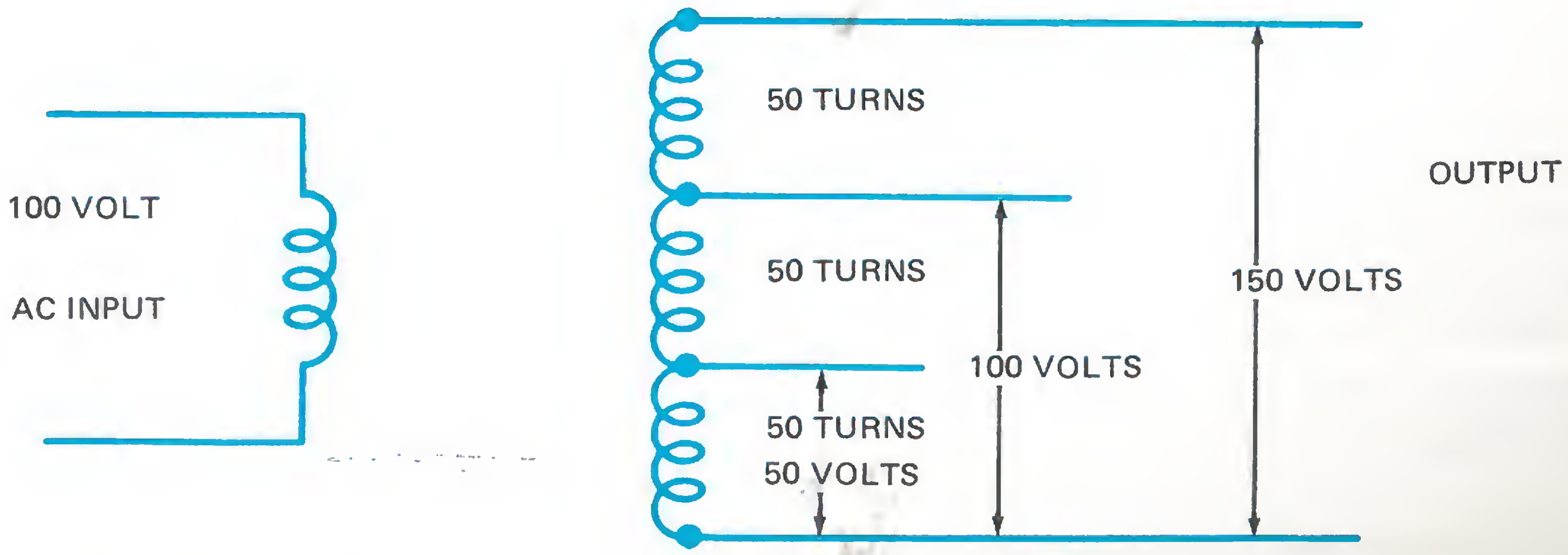


Fig. 6-9 Isolation Transformer With Tapped Secondary

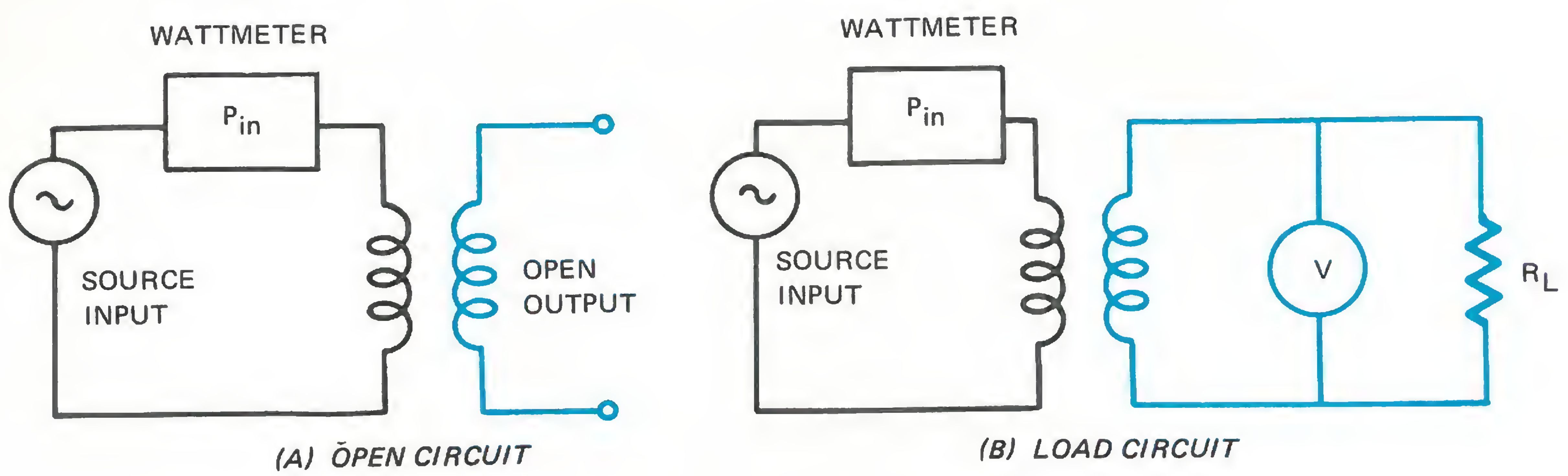


Fig. 6-10 Circuits To Determine the Losses In a Transformer

In the circuit in figure 6-10a, the power in the primary of the transformer is measured by the wattmeter. Since the secondary is open circuited, all of the power into the transformer is a loss. Therefore, the reading from the wattmeter gives the approximate core losses of the transformer.

In the circuit in figure 6-10b, there is an induced current flowing in the load resistor R_L. The output voltage can be measured across this resistor. Since power out is equal to

$$P = I^2R = \frac{V^2}{R} \qquad (6.9)$$

the corresponding output power can be determined. The power loss would then be the difference in the input and output power values.

$$P_{losses} = P_{in} - P_{out} \qquad (6.10)$$

The input power may also be measured as shown in the circuit in figure 6-10b and the power output across the load can be measured by means of another wattmeter. The difference in these power readings gives the power losses.

The power factor can also be determined when measuring losses of a transformer. Figure 6-11 gives a circuit that can be used to determine the power factor.

The *apparent power* into the transformer in figure 6-11 is given by

$$P_{app} = EI\ Va$$

where P_{app} = apparent power
E = voltage across primary
I = current in primary

The voltage and current can be read from the meters shown in figure 6-11. The real power into the transformer is read by the wattmeter.

The power factor (pf) is defined as the *cosine* of the angle between the real power and the apparent power shown by the right triangle diagram in figure 6-12.

The power factor can be multiplied by the real power to obtain the apparent power

$$pf\ (P_a) = P_R$$

Saturation is a term used with transformers. Saturation occurs when the domains of the magnetic material are completely aligned and a further increase in input current will not produce an increase in magnetic flux. Such a relationship will resemble the curve shown in figure 6-13.

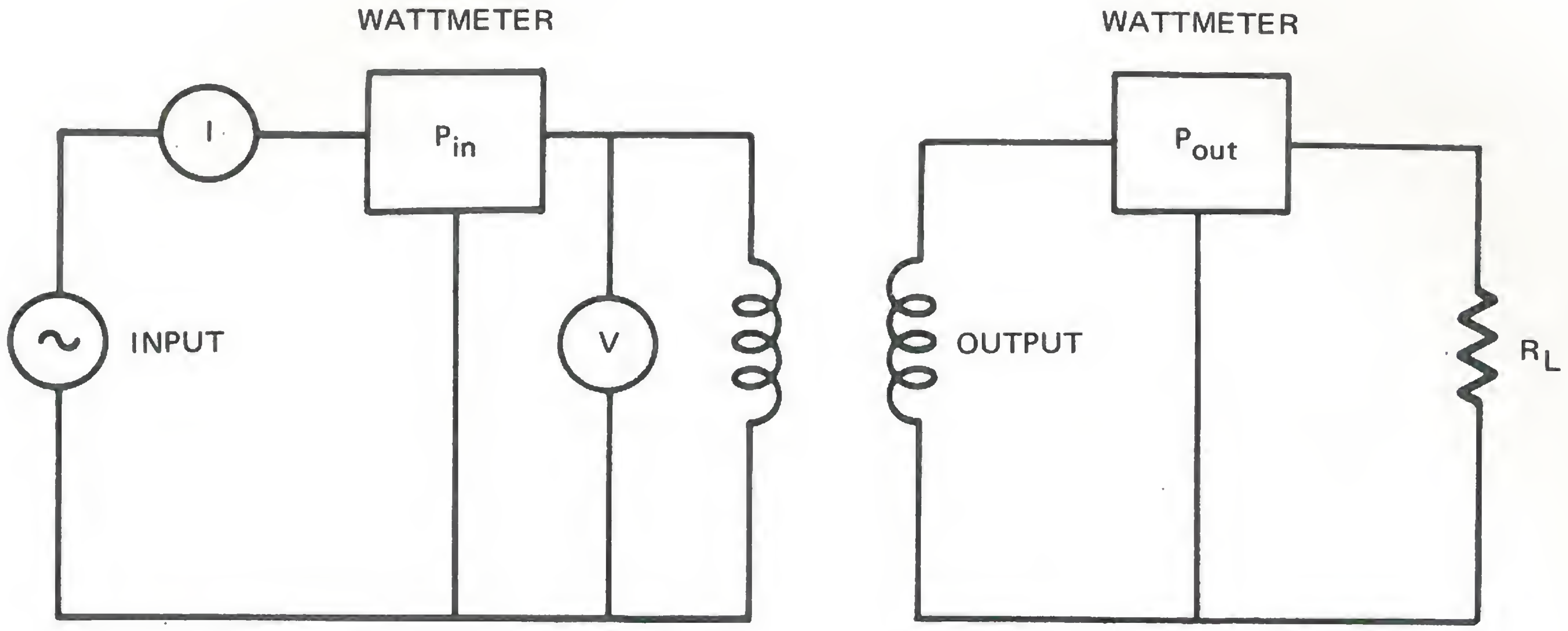


Fig. 6-11 Circuit To Determine the Power Factor Of a Transformer

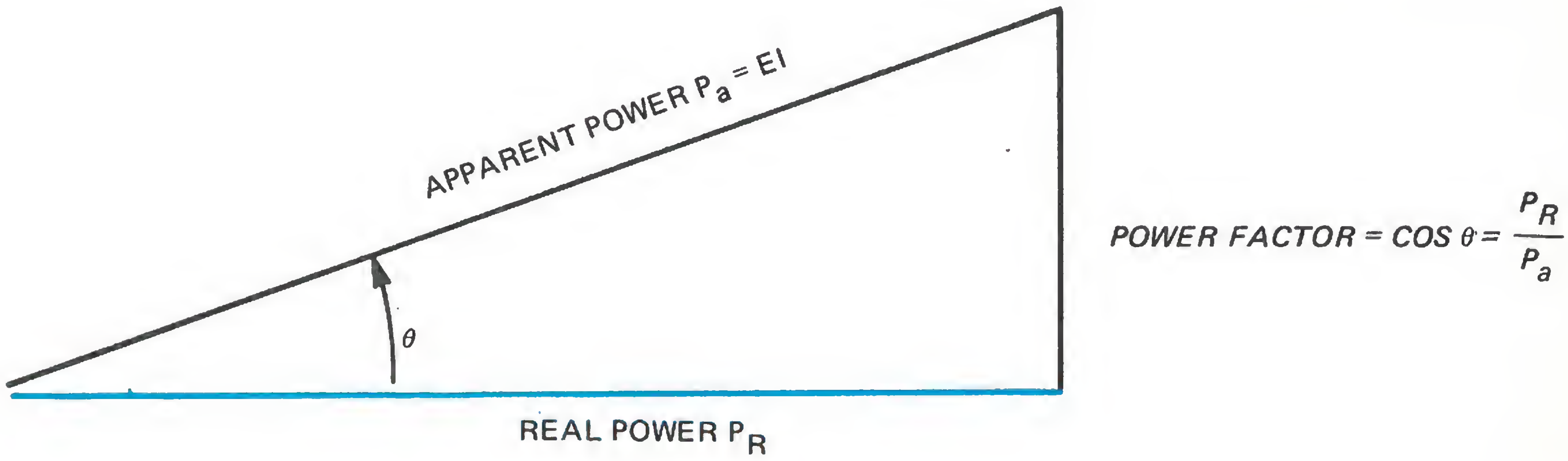


Fig. 6-12 Power Triangle

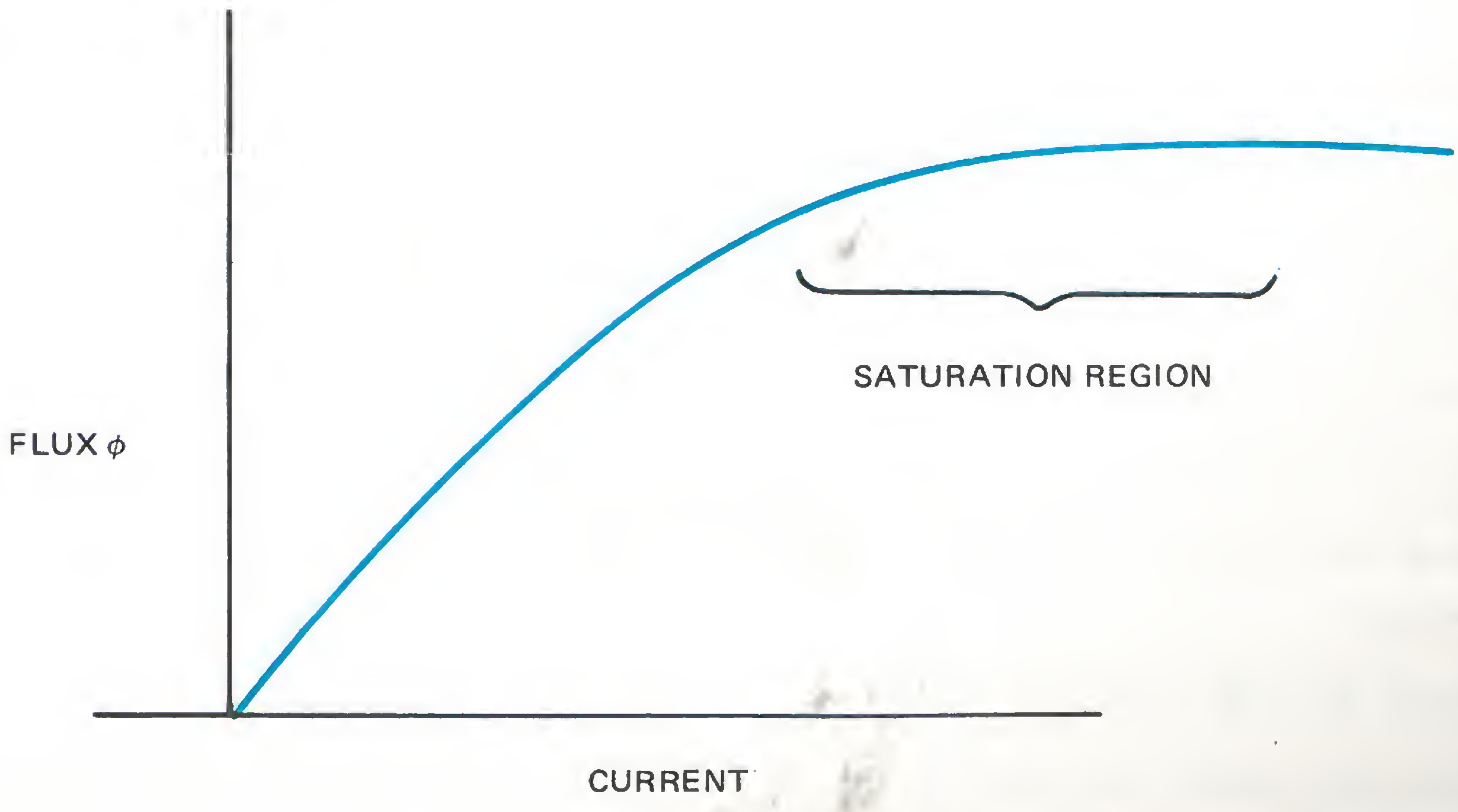


Fig. 6-13 Saturation Curve Of a Transformer

MATERIALS

1 Transformer — Primary 240/480 to 120/240, .050 kva 50, 60 Hz

1 Wattmeter, 0-50 watts

2 VOM meters

1 Audio generator 0-600k Hz

1 Variable transformer 0-115 volt output

1 1000Ω 25 watt

2 500Ω 25 watt

PROCEDURE

1. Connect the circuit in figure 6-14 with the output stepped up by a two to one ratio. Connect the audio generator to the input.

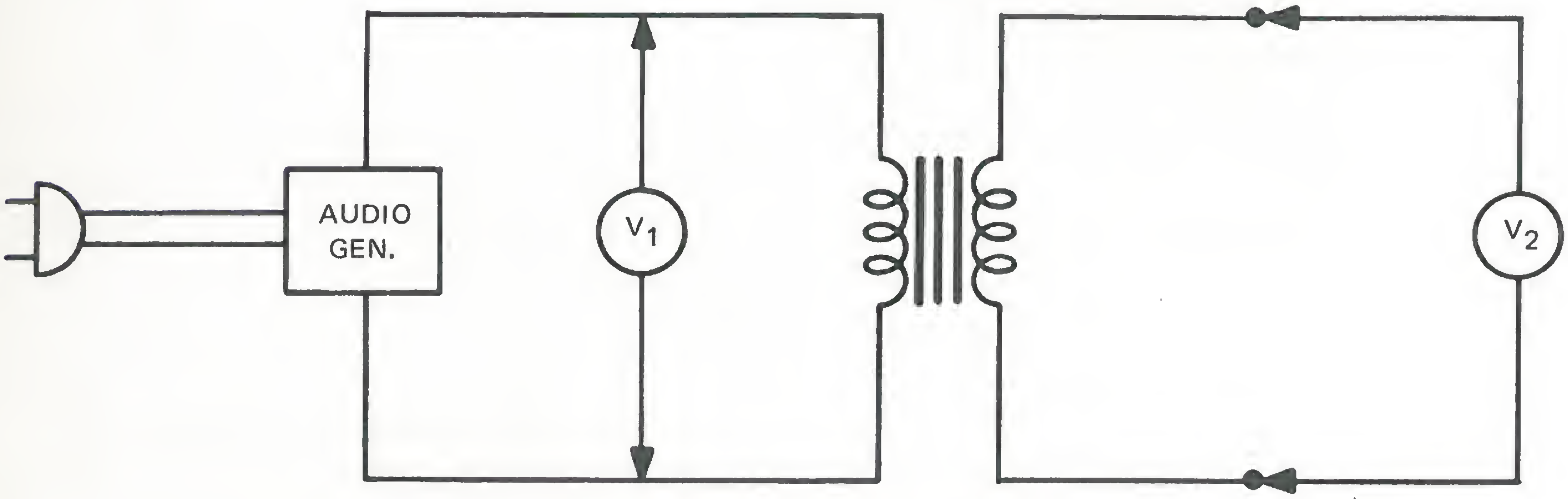


Fig. 6-14 Experimental Set Up I

2. With the output frequency of the signal generator at 0 Hz, record the input voltage V_1 and the output voltage V_2 in data table, figure 6-15.
3. Increase the frequency to 10 Hertz. Measure and record the voltages V_1 and V_2 in the table.
4. Increase the frequency to each value given in figure 6-15, and record the input and output voltage.
5. From the data, determine the turns ratio of the transformer for each frequency.
6. Reconnect the leads of the transformer so that the output is stepped down by a one to two ratio.
7. Repeat steps 2 through 5 and record the voltages in the data table.
8. Determine the turns ratio with the transformer hooked up this way for each frequency.
9. Change the circuit to look like the one in figure 6-16 with the output and input at equal potentials.
10. Increase the input voltage to 50 volts.
11. Record the power indicated by the wattmeter and the output voltage in the data table figure 6-17.

Freq.	0	10	35	60	600	6000
V_1						
V_2						
Turns Ratio						

Freq.	0	10	35	60	600	6000
V_1						
V_2						
Turns Ratio						

Fig. 6-15 The Data Tables

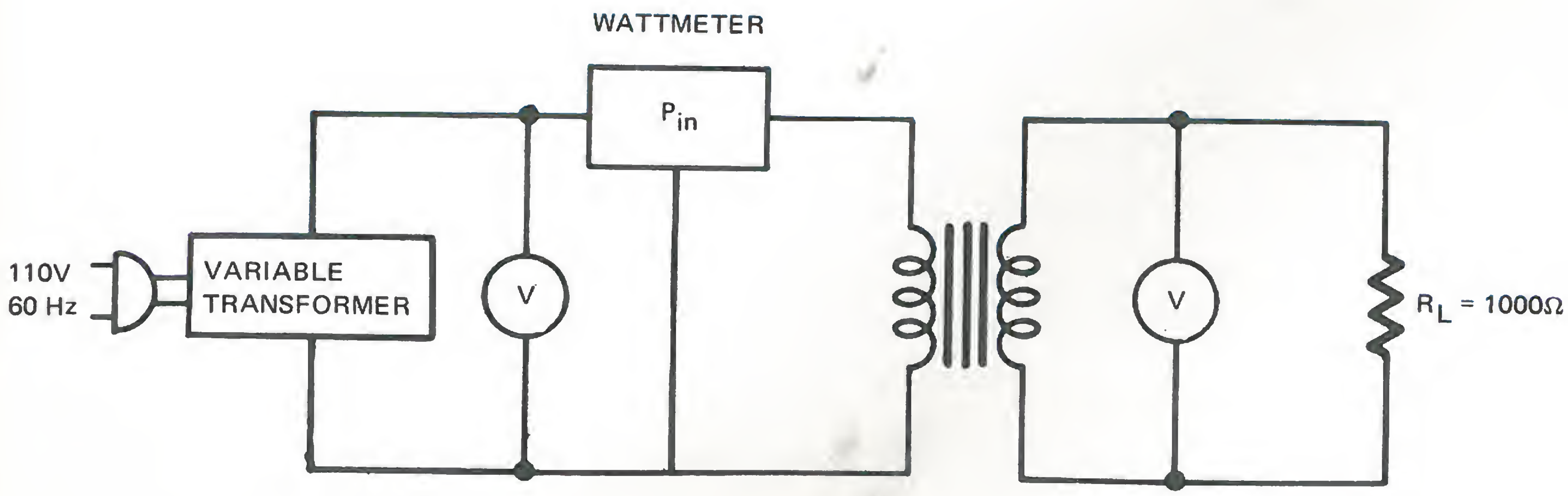


Fig. 6-16 Experimental Set Up II

12. Increase the input voltage to 100 volts or to the maximum output of the Variable transformer, whichever is smaller.
13. Repeat step 11.
14. Replace the load resistor with a 500 Ω resistor.
15. Repeat steps 10, 11, 12, and 13.

R_L = 1000 Ω

V_{in}	P_{in}	V_o	P_{out}	P_{loss}	Eff.	a
25						
50						
75						
95						

R_L = 500 Ω

V_{in}	P_{in}	V_o	P_{out}	P_{loss}	Eff.	a
25						
50						
75						
95						

R_L = 250 Ω

V_{in}	P_{in}	V_o	P_{out}	P_{loss}	Eff.	a
25						
50						
75						
95						

Fig. 6-17 The Data Tables

16. Place a 500 Ω resistor in parallel with the other 500 Ω resistor.
17. Repeat steps 10, 11, 12, and 13 for the equivalent 250 Ω 50 watt load.
18. Calculate the power out for each reading obtained.
19. Calculate the power losses for each reading.
20. Calculate the transformation ratio using $a = \frac{V_o}{V_{in}}$ for each reading.

ANALYSIS GUIDE. From the data it should be apparent that transformers do not transfer energy from one level to another without some power loss. Plot graphs of frequency versus transformation ratio using the data obtained in the data tables. From the data in figure 6-17, plot graphs of power out and power loss versus power in. Also plot efficiency and transformation ratio versus voltage in for each load resistor used.

PROBLEMS

1. A transformer substation is used to reduce the voltage to 3800 volts from a 132,000 volt line. The primary current is 38 amps. Determine the secondary current.
2. If additional transformers were used to reduce the above voltage from 3800 volts to 115 volts, determine the secondary current.
3. How does the voltage per turn on the primary compare with the voltage per turn on the secondary of a transformer?
4. A transformer is required to step up a voltage from 120 to 540 volts. How many turns are required on the secondary winding if the primary has 180 turns?

experiment 7 ENERGY STORAGE

The energy stored in a rotating flywheel is sufficient to drive a system for short periods of time after the power source is removed. In this experiment, some methods of energy storage will be examined.

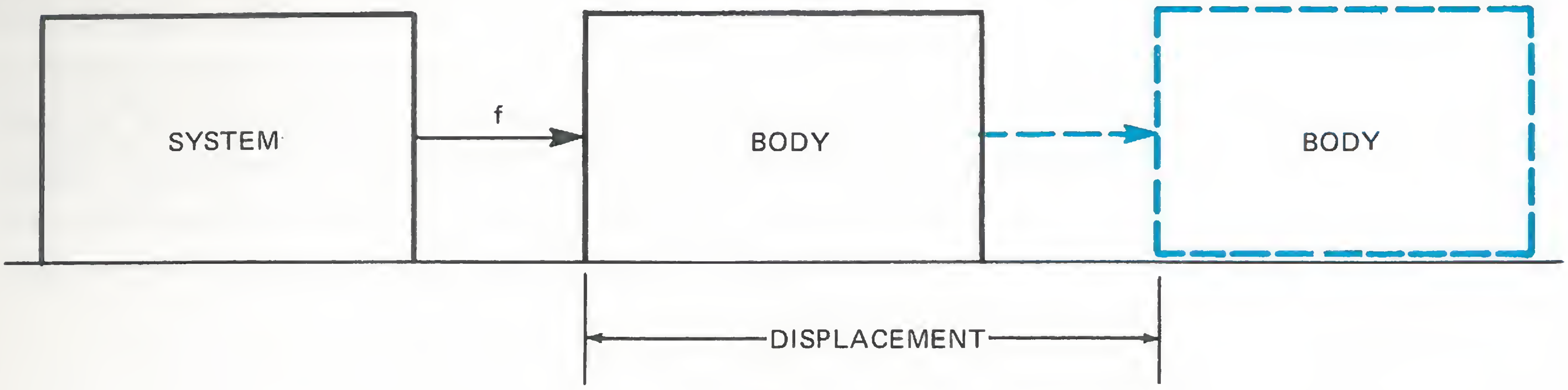


Fig. 7-1 Simple Translational System

Whenever a force acts so as to produce a displacement of a body, work is done on the body. A simple translational system is shown in figure 7-1. The work done by the system on the body in displacing it a given distance with a force is

$$\boxed{w = fd} \tag{7.1}$$

Note: When the displacement is zero, no work is done by the system. The work done by lifting a body against gravity can be calculated using this equation.

But, the force depends on the gravity, g, usually taken as 32.2 ft/sec^2 at sea level, and on the mass.

$$f = mg \tag{7.2}$$

So if the body is raised to a height, h in feet, the work in ft-lbs is

$$w = (mg)h \tag{7.3}$$

A simple rotational system is shown in figure 7-2. The work done by the system on the body in displacing it through a given distance is

$$w = fs \tag{7.4}$$

but, the distance, s, depends on the displacement angle and the radius of the circle,

$$s = \theta R.$$

Therefore, the work is

$$w = f(R\theta) \tag{7.5}$$

The term fR in equation (7.5) is torque; therefore, the final equation for the work done in a rotational system is

$$w = T\theta \tag{7.6}$$

The work done by the system in figure 7-3 in stretching or compressing the spring is

$$w = fs$$

but the distance is the length of deformation and may be calculated as

$$s = \ell_2 - \ell_1. \tag{7.7}$$

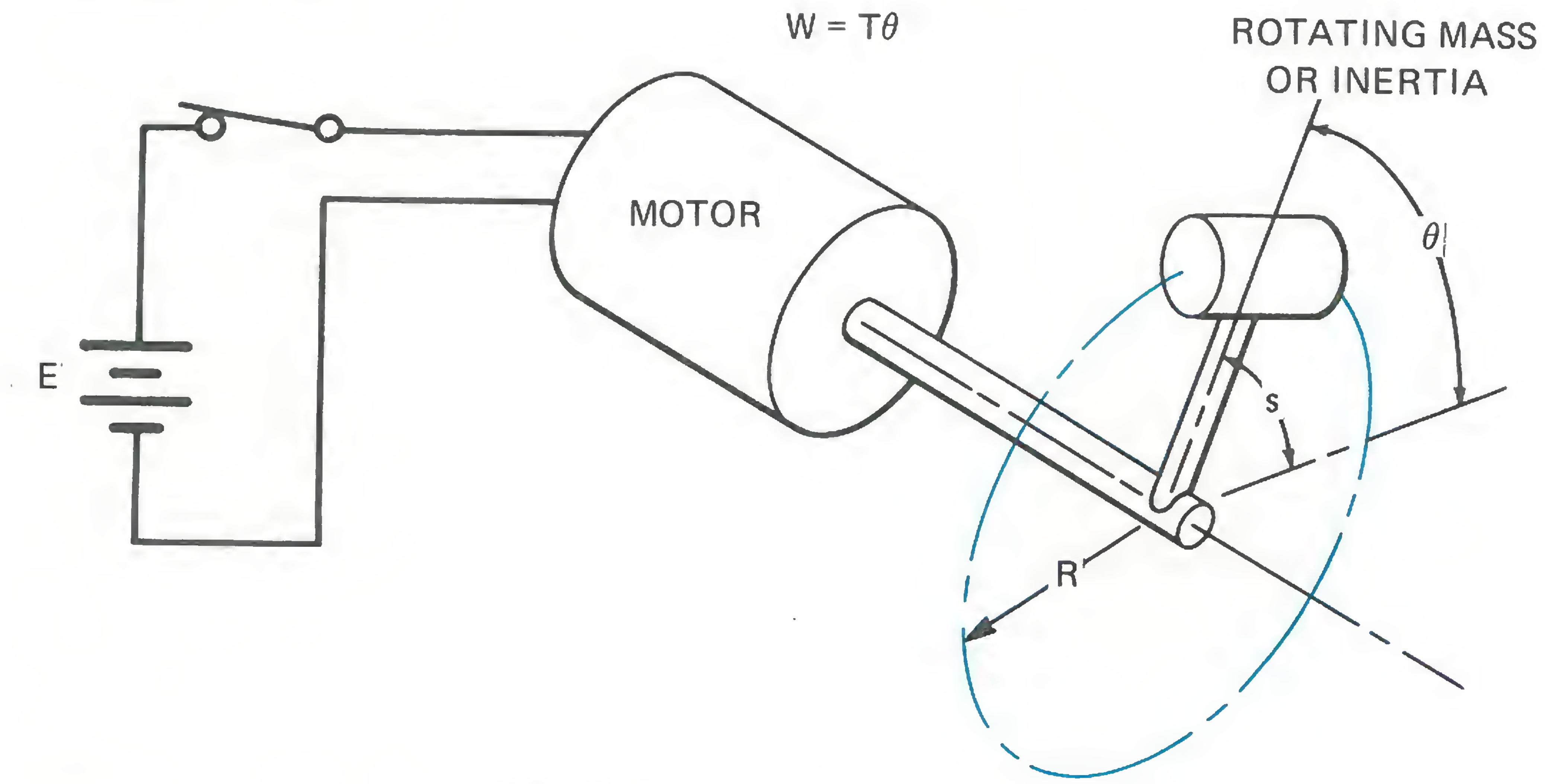


Fig. 7-2 A Simple Rotational System

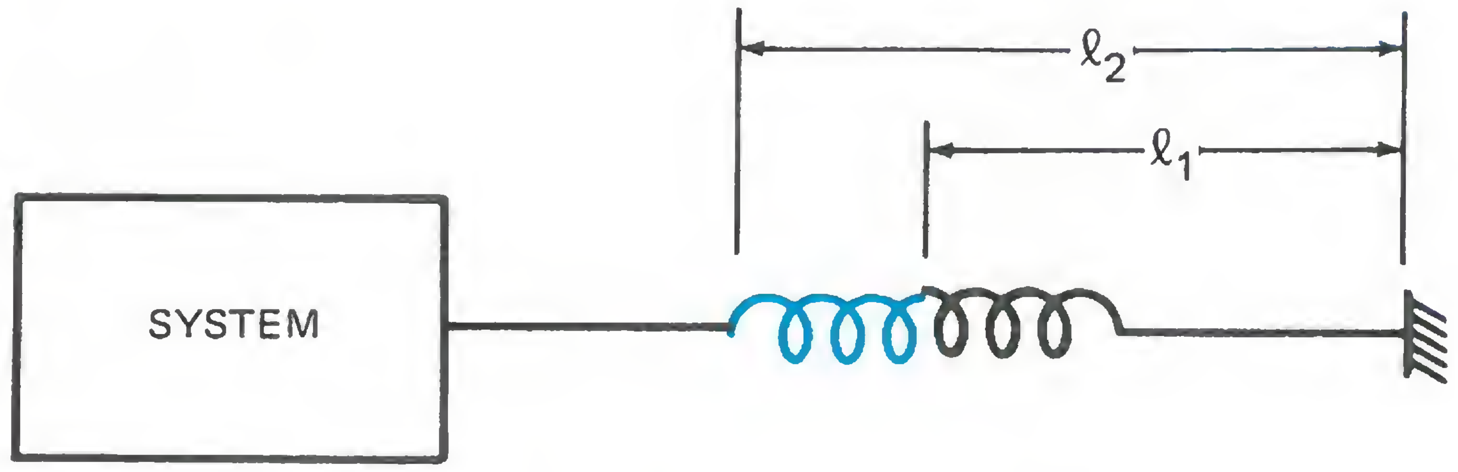


Fig. 7-3 Simple Spring System

Therefore, the work is

$$w = f(\ell_2 - \ell_1) \qquad (7.8)$$

where f is the average force.

The work done by the system in figure 7-4 in charging the capacitor is

$$w = Fs$$

but the force required to move a charge, Q in coulombs, from one point to another in a uniform electric field, E, is

$$f = QE \qquad (7.9)$$

where, Es = V, the voltage in volts.

Therefore, the work in joules is

$$w = QEs = QV \qquad (7.10)$$

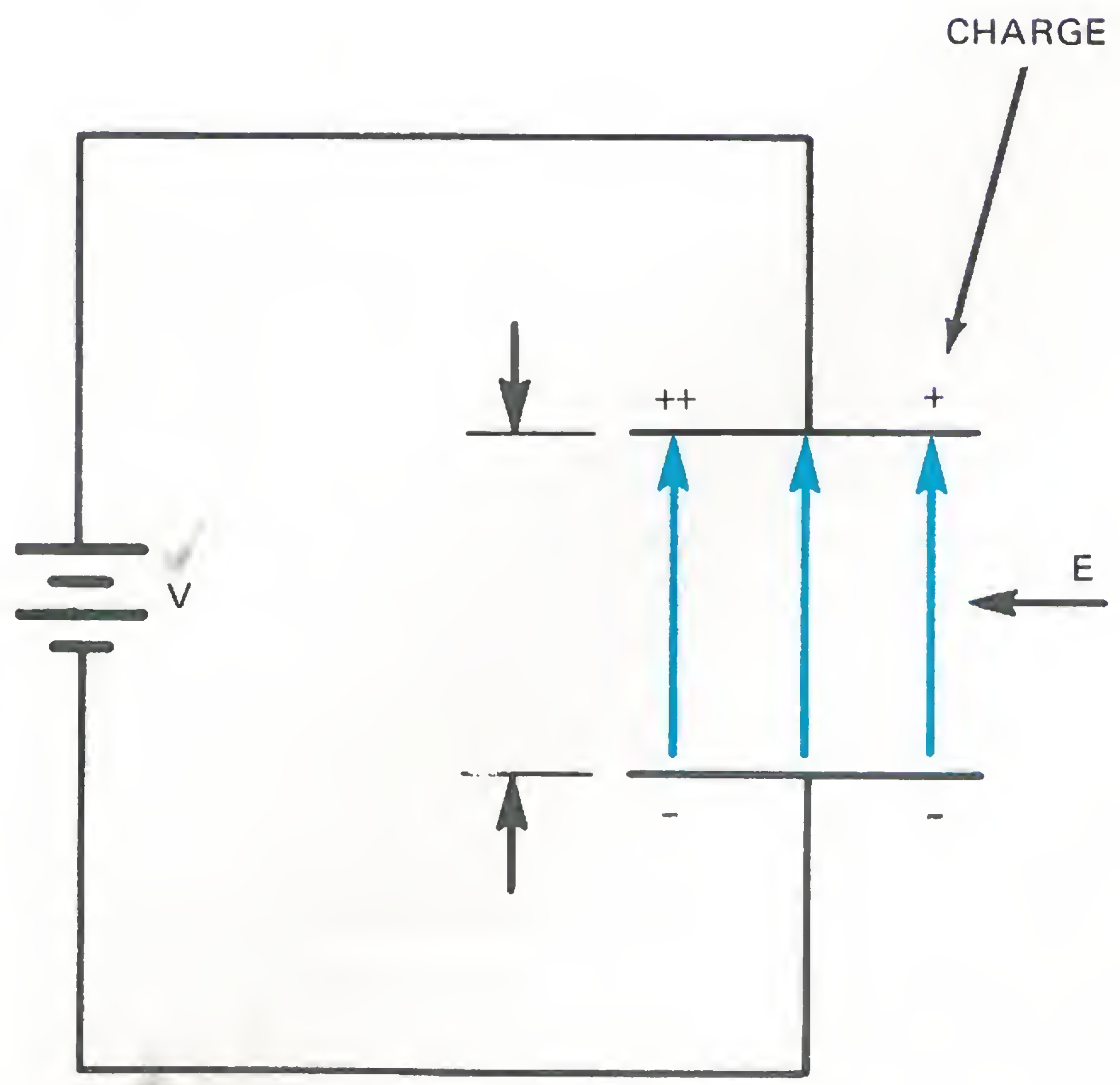


Fig. 7-4 Capacitor Charge Circuit

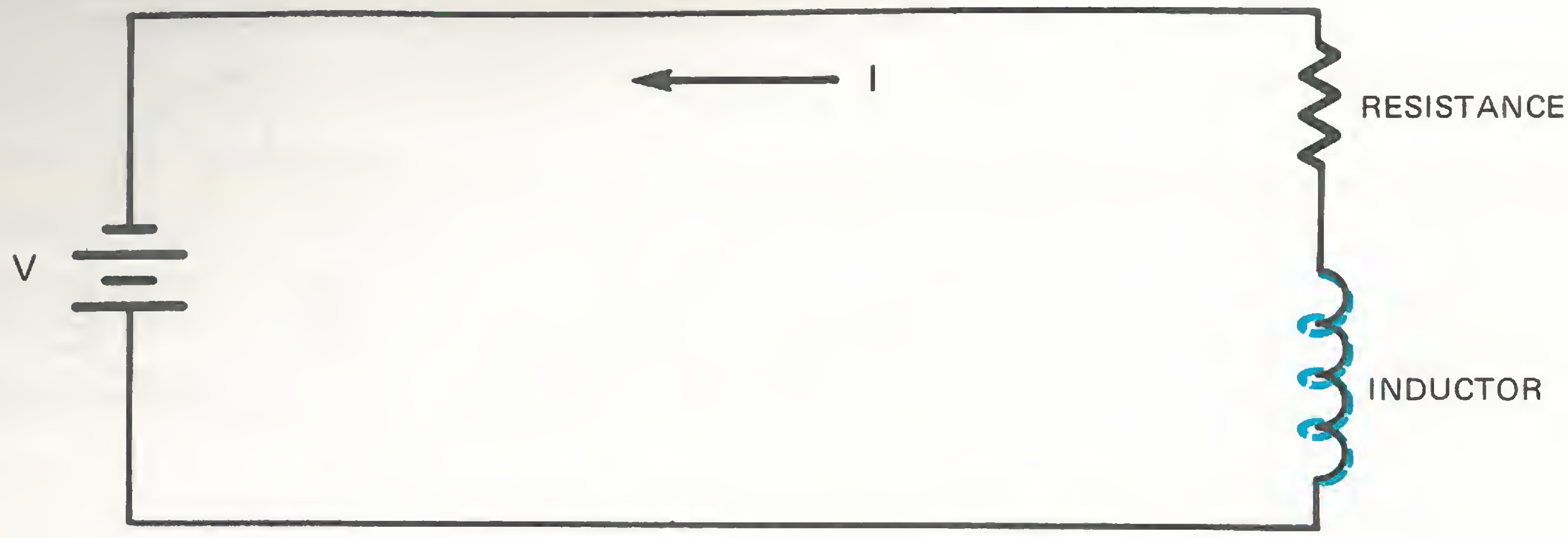


Fig. 7-5 Inductor Circuit

The work done by the system in figure 7-5 in charging the inductor is

$$w = fs$$

From equation 7.10, $w = QV$ and $Q = It$. Therefore, the work in joules is

$$w = IVt \qquad (7.11)$$

where I is the current and must be constant during the time t.

The time required to perform a task is just as significant as the work required. If given enough time, the smallest motor could lift the largest aircraft carrier.

However, if the task is to be carried out quickly, a motor whose output of work is rapid in terms of the total is required. The rate at which work is being done is termed *power.* Power is the time rate of doing work and is expressed as

$$P = \frac{w}{t} \qquad (7.12)$$

EXAMPLE: A 10-hp motor provides power for the elevator of a four story building. If the total weight of the loaded elevator is two tons, how long does it take to rise from the first floor to the third floor if the distance is 60 feet?

$$w = fs = 2000 \text{ lbs} \times 60 \text{ ft} = 120{,}000 \text{ ft-lbs}$$

$$P = 10 \text{ hp} \times 550 \frac{\text{ft-lb/sec}}{\text{hp}} = 5500 \text{ ft-lbs/sec}$$

$$t = w/P = \frac{120{,}000 \text{ ft-lbs}}{5500 \text{ ft-lb/sec}} = 21.8 \text{ sec}$$

Energy is the ability to do work. The basic unit of measurement of energy is the same as that for work.

The two broad classifications of mechanical energy are *kinetic energy* and *potential energy.* Some other forms of energy, besides mechanical energy, are: heat, electrical, magnetic, chemical and nuclear.

A body may possess energy by virtue of its mass, inertia, spring constant, inductance or capacitance. The energy acquired by a body as a result of work done on it by a system can be stored and returned to the system at a later time.

The two types of energy storage are: *static storage* and *dynamic storage. Static storage* of energy occurs within bodies that are *displaced* while *dynamic storage* of energy occurs within bodies that are *in motion.*

The energy stored in a mass because of its position may be considered as static energy. The energy stored in a capacitor

because of a stationary charge may be considered as static energy. Also, the energy stored in a spring because of a stationary force is considered as static energy.

The energy stored in a mass because of its motion may be considered as dynamic energy. The energy stored in an inductor because of the movement of charges through it may also be considered as dynamic energy. The dynamic energy, DE, stored in the mass of the body in figure 7-2 is the sum of the work done on it.

$$DE = \Sigma w$$
$$DE = \Sigma fs.$$

But, the force is

$$f = ma$$

and the distance is

$$s = \frac{1/2\,(V^2 - V_o{}^2)}{a} = \frac{1/2\,V^2}{a} \text{ if } V_o = 0$$

Therefore, the

$$DE = m\cancel{a}\,\frac{1/2\,V^2}{\cancel{a}} = 1/2\,mV^2 \qquad \textbf{(7.13)}$$

The static energy stored in a mass of the body because of its position is the sum of the work done on it:

$$SE = \Sigma w$$
$$SE = \Sigma fs.$$

But, the force is

$$f = ma$$

and if the distance is the height, h, therefore,

$$SE = mgh \qquad \textbf{(7.14)}$$

The dynamic energy stored in the rotating mass (inertia, I) in figure 7-2 is the sum of the work done on it:

$$DE = \Sigma w$$
$$DE = 1/2\,mV^2$$

But, the velocity $V = \omega R$. Therefore,

$$DE = 1/2\,m\,(\omega R)^2 = 1/2\,(mR^2)\,\omega^2$$

where mR^2 is the moment of inertia. Therefore the DE is

$$DE = 1/2\,I\omega^2 \qquad \textbf{(7.15)}$$

The static energy stored in the spring with a static force applied in figure 7-3 is the sum of the work done on it:

$$SE = \Sigma w$$
$$SE = \Sigma fs$$

But, the average force is

$$f = 1/2\,(f_2 - f_1).$$

Therefore

$$SE = 1/2\,f_2(\ell_2 - \ell_1)$$

if $f_1 = 0$

But $\ell_2 - \ell_1$ is the deformation, x, and

$$SE = 1/2\,f_2x.$$

The spring constant, k, of the spring is

$$k = f_2/x$$

if $f_1 = 0$. So we have

$$f_2 = kx$$

or $$SE = 1/2\,kx^2 \qquad \textbf{(7.16)}$$

The static energy stored in the capacitor (with a constant charge) in figure 7-4 is the sum of the work done on it:

$$SE = \Sigma w$$
$$SE = \Sigma QV$$

but, the charge of the capacitor is

$$Q = CV$$

and the average voltage is

$$V = 1/2\,(V_2 - V_1)$$

so $\quad Q = (1/2 V_2)C$

if $\quad V_1 = 0$

Therefore

$$SE = 1/2\ CV_2{}^2 \qquad (7.17)$$

The dynamic energy stored in the inductor (with charges flowing through it) in figure 7-5 is the sum of the work done on it:

$$DE = \Sigma w$$

But since the work is

$$w = Pt = IVt$$

for constant values of I

then $DE = \Sigma IVt$.

But $\quad I = 1/2\,(I_2 - I_1)$

or $\quad I = 1/2\ I_2$ if $I_1 = 0$

and $\quad V = L\dfrac{I_2 - I_1}{t} = L\dfrac{I_2}{t}$ if $I_1 = 0$

so $\quad DE = 1/2\ LI_2{}^2. \qquad$ **(7.18)**

The total amount of energy in a system isolated from its surroundings always remains constant although energy transformations from one form to another may occur within the system. However, dissipative components, resistance, friction, etc. convert energy into heat. The heat generated is usually considered to be a loss. The efficiency of a system is determined by

$$\%\ \text{Eff.} = \frac{w_o}{w_{in}} \times 100 = \frac{P_o}{P_{in}} \times 100 \qquad (7.19)$$

MATERIALS

1 Capacitor 1 μF, 400 working volts

1 Capacitor 2μF, 400 working volts

1 Resistor, 10k 2 watt

1 Resistor, 100k 2 watt

1 Strip chart recorder

1 Switch, SPDT

PROCEDURE

1. Construct the experimental circuit shown in figure 7-6 using the 1μF capacitor.
2. Set the speed of the strip chart recorder to 10 cm/sec.
3. Set the sensitivity of the strip chart recorder to 20 volt/cm.
4. Set the voltage, E, to 50 volt DC.

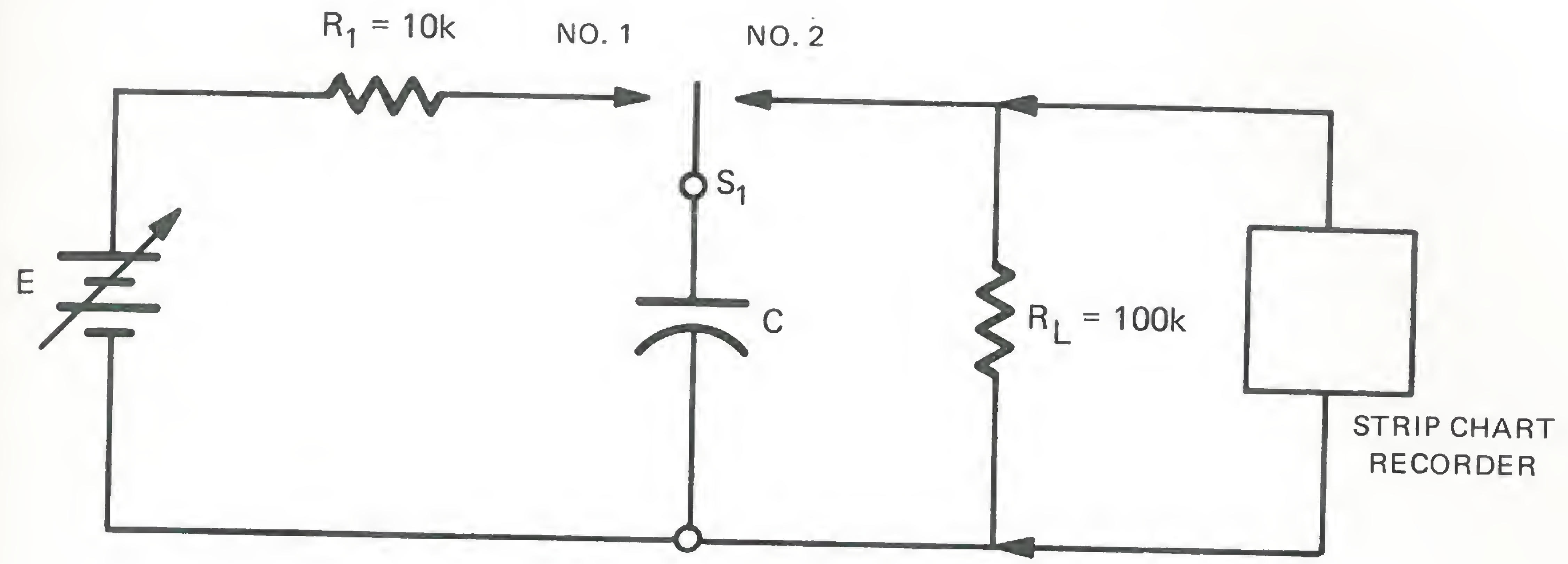


Fig. 7-6 Experimental Circuit

5. Switch S_1 to position 1 for one minute.
6. Engage the motor of the strip chart recorder so that chart paper moves.
7. Switch S_1 to position 2 for one second.
8. Calculate the time at 1RC, 2RC, 3RC, 4RC and 5RC using the following equation
   $$t = RC \text{ seconds}$$
9. Record this data in data table figure 7-7 as t.
10. On the strip chart recorder trace, mark the time intervals at 0, 1RC, 2RC, 3RC, 4RC and 5RC. The time interval on the trace is determined using the following equation.
   $$\text{No. of cm} = 10 \text{ cm/sec } (t)$$

$c = 1 \mu F$, $E = 50$ volts

	t	V_c	P_c
0 RC	0 sec		
1 RC			
2 RC			
3 RC			
4 RC			
5 RC			

Fig. 7-7 The Data Table, Part I

$c = 1 \mu F$, $E = 100$ volts

	t	V_c	P_c
0 RC			
1 RC			
2 RC			
3 RC			
4 RC			
5 RC			

Fig. 7-7 The Data Table, Part II

11. At the time intervals marked in step 10, determine the voltage using
$$V_c = 20 \text{ volts/cm (deflection in cm)}$$
12. Record this data in data table figure 7-7 as V_c.
13. Calculate the power at each time interval using the equation $P_c = V^2 \div R_L$
14. Repeat steps 1 through 14 for E of 100 volts. Record in data table, Part II.
15. Repeat steps 1 through 15 for c of $2\mu F$. Record in data table, Parts III and IV.

ANALYSIS GUIDE. Plot a graph of the power, P_c, versus time, t, for each data table. Plot a graph of the voltage, V_c, versus time, t, for each data table. Compare the work done on the capacitor, $1/2\ CE^2$, with the energy delivered by the capacitor. The energy delivered by the capacitor is the area under the power curve plotted in this analysis.

PROBLEMS

1. Calculate the work involved in lifting a 2000-lb. weight up a 100-ft. oil derrick.
2. Calculate the work involved in charging a 1 Henry inductor with 10 amps for 1 hour.
3. Calculate the power required to lift the weight in problem 1, 50 feet in 2 seconds.

4. Calculate the dynamic energy stored in a flywheel that has a moment-of-inertia of 1000 slugs-ft^2 and an angular velocity of 100 rad/second.

5. Calculate the static energy stored in a 1μF capacitor that is charged to 100 volts DC.

c = 2μF, E = 50 volts

	t	V_c	P_c
0 RC			
1 RC			
2 RC			
3 RC			
4 RC			
5 RC			

Fig. 7-7 The Data Table, Part III

c = 2μF, E = 100 volts

	t	V_c	P_c
0 RC			
1 RC			
2 RC			
3 RC			
4 RC			
5 RC			

Fig. 7-7 The Data Table, Part IV

experiment 8 ENERGY STORAGE IN RELAY SPRINGS

INTRODUCTION. When the energizing source of a relay coil is interrupted, the relay contacts open. In this experiment, the static energy stored in the relay springs will be investigated.

DISCUSSION. A relay is an electrically operated switch that is classified as an electro-mechanical device.

Two Relay Selection Criteria are:

1. Switching operation determines the number, type and arrangement of the contacts.
2. Power source to actuate the relay determines the design of the coil and magnetic circuit.

The auxiliary specifications for selecting a relay are:

1. size and weight
2. operating life
3. insulation breakdown
4. resistance to shock and vibration
5. environment

The operation of the relay shown in figure 8-1a is as follows:

As the current through the coil is increased, the mmf (magnetomotive force) increases which causes an increase of magnetic lines of force in the core of the relay. When the force of attraction acting on the armature is sufficient to overcome the spring tension, the armature moves downward closing the contacts (energizing the relay). The current value that will cause the contacts to close is called the *pull-in-current* of the relay. The force acting to close the air gap can be found by

$$f = 1.4 \times 10^{-8} B^2 A \qquad (8.1)$$

where f is in pounds, B is the flux density in the air gap in lines/sq.in., and A is the cross-sectional area of the air gap in square inches.

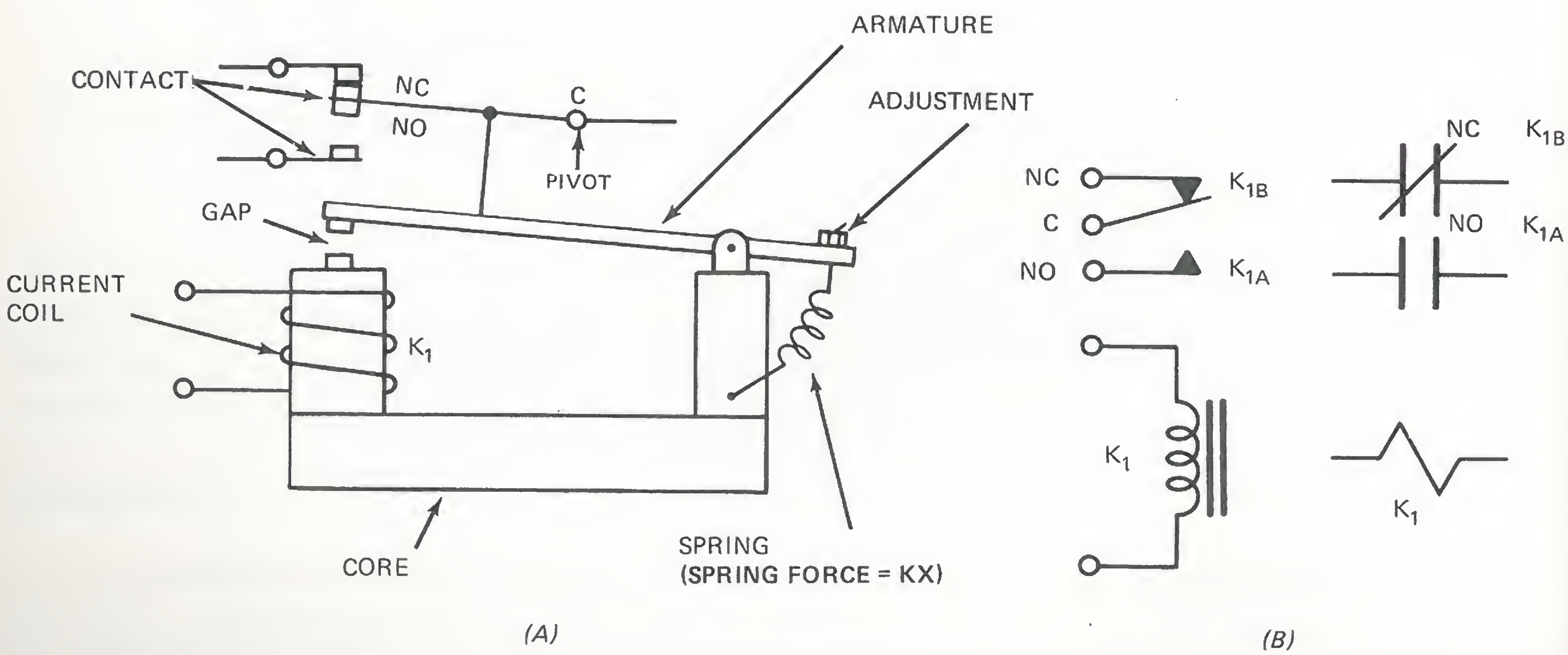


Fig. 8-1 The Basic Relay

The force applied to the armature required to close the contacts is

$$f = kd \qquad (8.2)$$

where f is in pounds, d is the relative deformation of the spring in inches, and k is the spring constant in lbs./in. When the armature closes, the flux density increases because the air gap length has been decreased reducing the total reluctance of the magnetic circuit. Since the flux density has increased, the force acting on the armature increases. If we decrease the current in the coil, the flux density will decrease, decreasing the force exerted by the magnetic field upon the armature.

When the force due to static energy storage excited on the armature by the spring is greater than the magnetic force, the relay armature moves upward opening the relay contacts (de-energizing the relay). The current value that will allow the contacts to open is called the *drop-out current.* The drop-out current is much less than the pull-in current. The difference between the pull-in current and the drop-out current is called the *differential current* of the relay.

The force holding the contacts closed is called the contact pressure and is approximately 1 to 2 oz. Prior to contact release, the static energy stored in the spring is

$$SE = 1/2\ K\ d^2 \qquad (8.3)$$

The schematic symbol for the relay is represented in figure 8-1b.

Relays are usually rated according to their contact and coil characteristics. First, let's look at the coil ratings. The coil of a relay is usually rated as follows:

1. **Voltage.** Coils are rated such that the relay will reliably energize.

   a. AC relays will energize at approximately 85% of their nominal rated coil voltage.

   b. DC relays will energize at approximately 75% of their nominal rated coil voltage.

Standardized coil ratings are:

6, 8, 10, 12, 24, 32, 48, 60, 115, 230 AC or DC and 440 volts AC.

2. **Current.** The nominal current rating of a relay is the normal operating current and not necessarily the current flowing to energize the relay.

   a. In AC relays, the initial or inrush current is usually about 1-2/3 times greater than the normal current. The amount of current drawn by the coil depends mainly on the impedance of the circuit which is chiefly reactive: The impedance of the coil is:

$$Z^2 = R^2 + X_L{}^2 \qquad (8.4)$$

   where Z is the impedance of the coil in ohms, R is the resistance of the coil wire and X_L is the inductive reactance at the AC line frequency. The coil current is then determined as follows:

$$I = E/Z \qquad (8.5)$$

   where I is the relay current, E is the relay voltage and Z is the impedance of the relay coil.

   b. In DC relays the coil current is dependent on the coil resistance only and is independent of armature position.

$$I = E/R \qquad (8.6)$$

3. **Differential Current.** The operate current of a relay is determined by the length of the air gap and the spring-restoring force or the armature. The release current of the relay is much less, since the reluctance in the magnetic circuit has been reduced. Consequently, the magnetic flux and pull on the armature is increased. The differential current, which is the difference between operate current and release current, may be determined as follows:

$$I_D = I_o - I_r \qquad (8.7)$$

where I_D is the differential current in amperes, I_o is the operate or pull-in current and I_r is the release current.

4. **Power.** The maximum continuous power input to a given relay coil is limited by the maximum temperature that the coil insulation can withstand without breakdown. Generally, the maximum temperature is approximately 200°F. AC relays usually run higher than DC relays of the same type, not only because they are less power-sensitive, but also because, when AC current is used, eddy current and hysteresis heating is present.

The power required by the coil can be calculated as follows:

$$P = I^2R \quad \text{AC or DC} \qquad (8.8)$$

$$P = EI \cos\theta \quad \text{AC} \qquad (8.9)$$

where P is the power in watts, I is the current in amperes and R is the resistance of the coil in ohms.

5. **Operate and Release Time.** The operating speed of the relay is determined by the rate of flux build-up combined with armature closing time.

a. AC: 5 to 70 milliseconds.

b. DC: 15 to 70 milliseconds.

Usually DC relays are slower in operation than AC relays. Relay operating speed can be changed by varying the spring tension, the armature-core gap, and the coil inductance if AC is used.

The characteristics of the relay's contacts are rated as follows:

1. **Relay Contact Arrangement.** Relays are available in many forms with contact arrangements ranging from a single pair, to make or break a single circuit, to stacks of dozens to handle a number of independent circuits. For most purposes, however, there are four basic contact groups, as shown in figure 8-2.

2. **Contact Ratings.** Successful closure of relay contacts demands that contacts close clean, with minimum bounce or chatter, and that they be sufficiently large, of the correct material and actuate with sufficient force to prevent arcing and welding with initial value of current.

a. **Contact Resistance.** The contact resistance should be sufficiently low to carry the steady current without excessive heating or voltage drop. The normal value of contact resistance is 15 to 50 milliohm.

b. **Voltage Rating.** The contact gap usually determines the maximum voltage that can be impressed across the open contacts without arcing.

c. **Current Rating.** The current rating of the contacts depends on the material used, the diameter of the points, contact pressure, thermal conductivity, and contact gap.

d. **Typical rating of relay contacts are:** 6 amps, 115 volts, 60 Hz, AC non-inductive: 3 amps, 115 volts, DC.

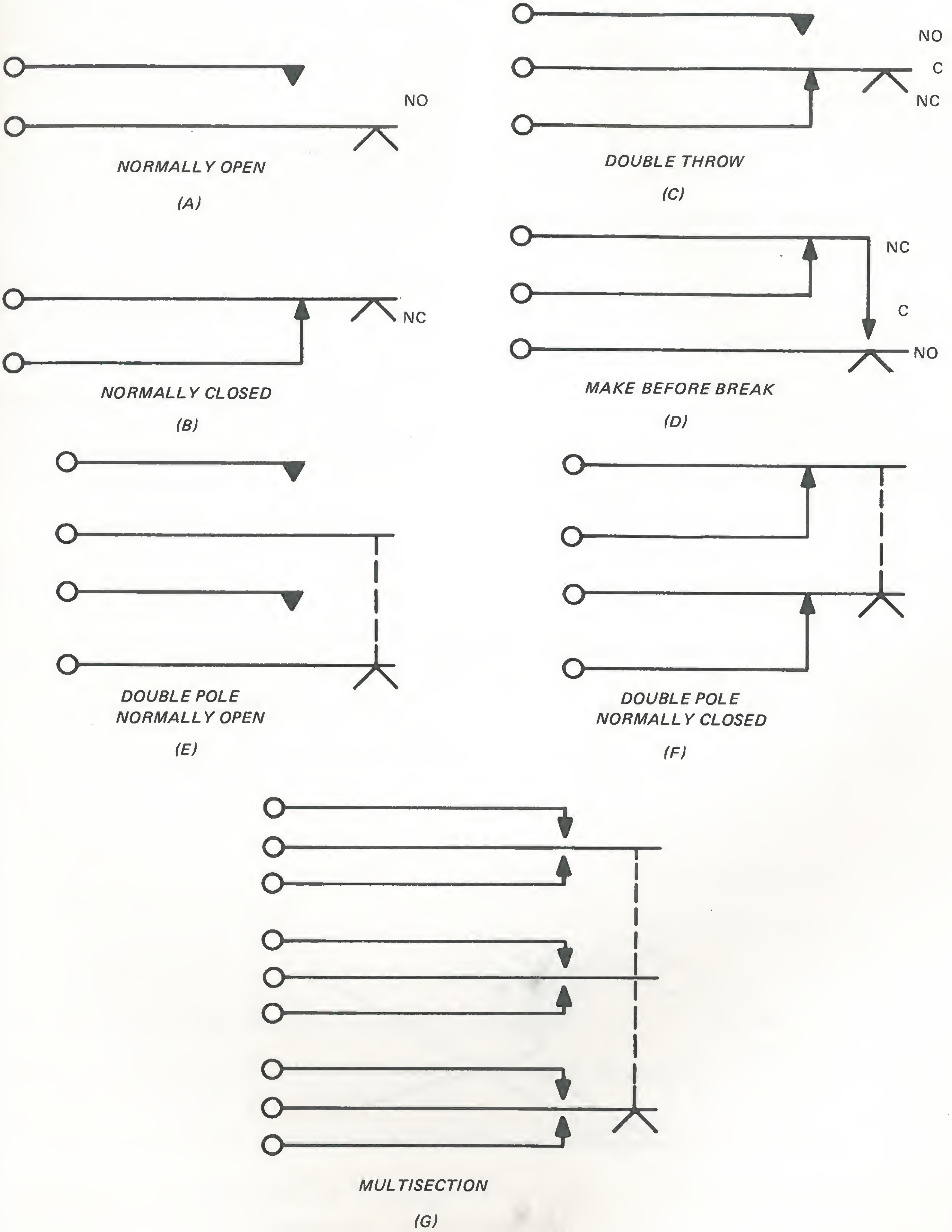


Fig. 8-2 Relay Contact Rating

The ideal contact material should have high electrical and thermal conductivity, high melting and vaporization temperatures, and high resistance to mechanical wear and should have no tendency to form an oxide or tarnish film. The use of the relay will determine the type contact required. For relay contacts of 3/16" in diameter and an air gap of 0.025 inches, a few applications are:

Silver Contacts — Low power applications, 4-6 amps of current

Palladium — Medium power application, 10-15 amps of current

Palladium — Iridium — Medium power application, 10-15 amps. Severe mechanical operating conditions.

Tungsten — Low power applications, 3-5 amps high voltage.

Note: *Currents of 20 amps or more usually require two gaps in series or double break contacts.*

3. **Relay Enclosures.** Relay contacts and coils are enclosed in various ways. General purpose relays are installed in a steel knockout box. When dust, foreign particles or moisture is present, relays are enclosed with a glass cover and a bakelite base. For severe conditions, the relay may be *hermetically sealed.* The hermetically sealed relay is shown in figure 8-3.

The life expectancy of relays is estimated conservatively at one million operation. Some conditions that reduce relay life are: contact current, overloading, arcing of contacts, excessive coil voltage, improper contact gap or spring pressure and improper maintenance.

The general classification of relays is as follows:

Heavy duty (contactors)

Midget

Miniature

Industrial Power

Low voltage, low current

Small size and weight, low current

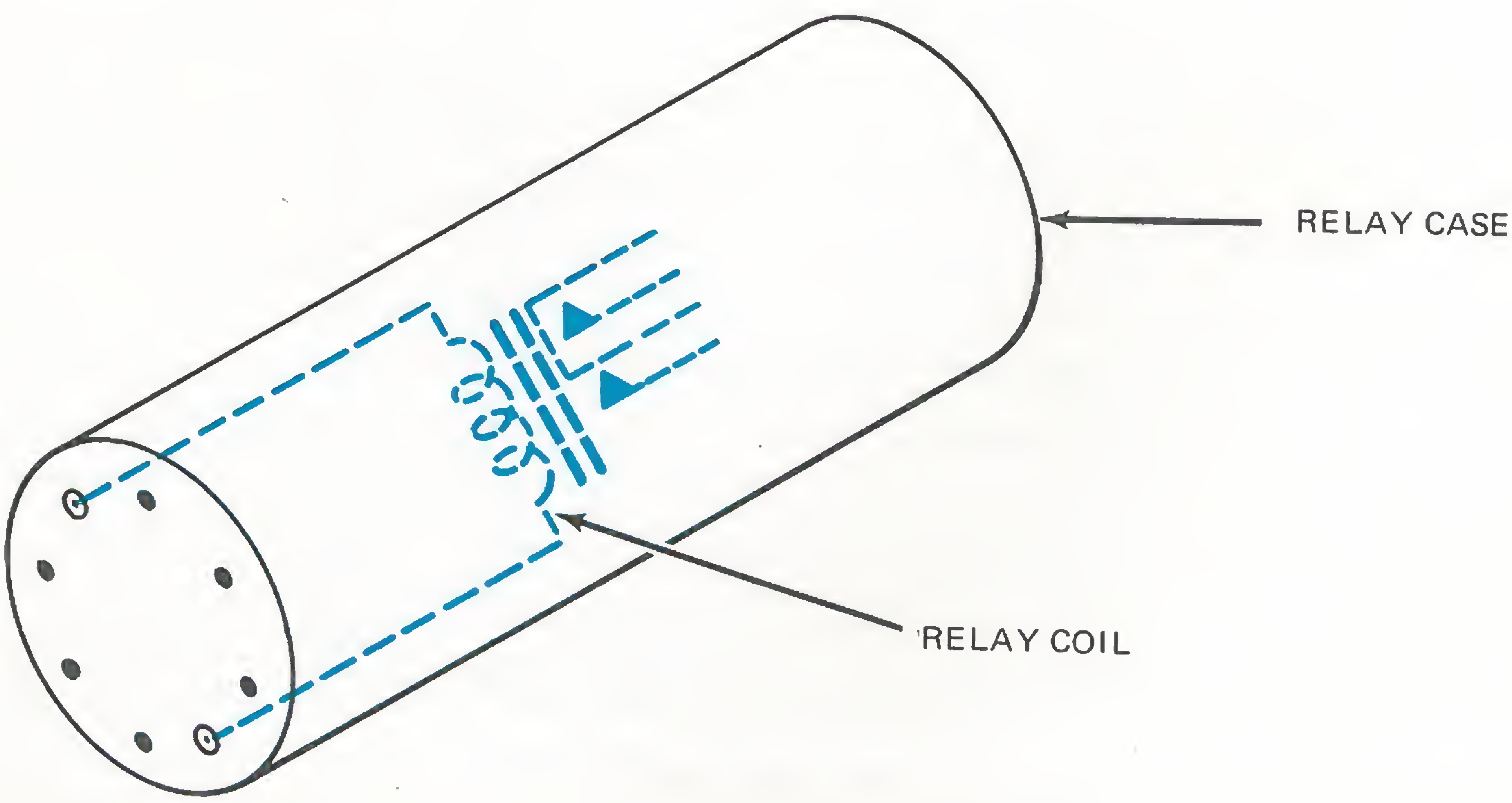


Fig. 8-3 Hermetically Sealed Relay

MATERIALS

1 Relay, 115 volt AC, open enclosure

1 Ring stand and clamp assembly

1 Scale, 0-10 ounces

1 Spring, steel 1/8" by 3/4"

1 Spring, steel 1/8" by 1-3/4"

1 Ammeter 0-150 mA

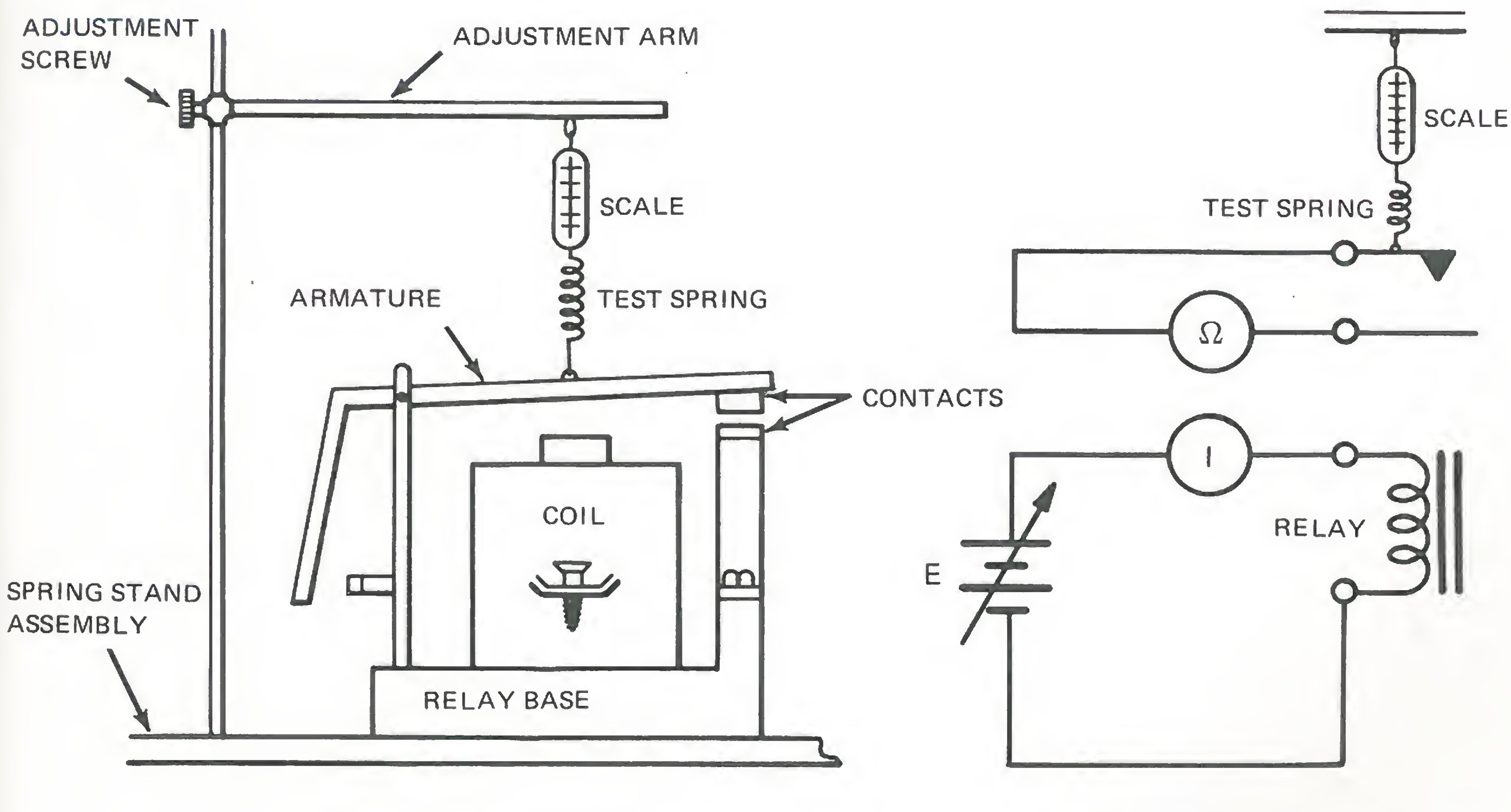
1 Ohmmeter

1 Supply, DC, 0-30 volts @ 1 ampere

1 Scale, 0-1"

PROCEDURE

1. Construct the experimental set-up shown in figure 8-4 using the 3/4" spring.



(A) MECHANICAL SCHEMATIC *(B) ELECTRICAL SCHEMATIC*

Fig. 8-4 Experimental Set-Up

2. Apply coil voltage until relay contacts are closed.
3. Adjust arm position for a scale reading of 1 ounce. Measure and record the test spring deflection in data table, figure 8-5A, as d.
4. Calculate the spring constant as k = f/d and record these data in figure 8-5A as k.
5. Calculate the energy stored in the spring as SE = $1/2kd^2$.
6. Decrease the current through the coil until relay contacts open.
7. Read and record the current in data table, figure 8-5A.

Spring	Force, f	Current, I	Defl., d	Spring Constant k	Energy Storage SE
3/4 in.	1 oz.				
	2 oz.				
	4 oz.				
	6 oz.				
	8 oz.				
	10 oz.				
1-3/4 in.	1 oz.				
	2 oz.				
	4 oz.				
	6 oz.				
	8 oz.				
	10 oz.				

Data Table 8-5A Relay Opening

Spring	Force	Current
3/4 in.	1 oz.	
	1.5 oz.	
	2.0 oz.	
	2.5 oz.	
	3.0 oz.	

Data Table 8-5B Relay Closure

8. Repeat steps 1 through 5 for spring readings of 2, 4, 6, 8 and 10 ounces.
9. Repeat steps 1 through 6 for the 1-3/4" spring.
10. With the relay voltage zero and the 3/4" spring installed, adjust the arm for a scale reading of 1 ounce.
11. Increase the current through the coil until relay contacts close.
12. Read and record the current in data table, figure 8-5B.
13. Repeat steps 8 through 10 for spring readings of 3, 4, 5 and 6 ounces.

ANALYSIS GUIDE. Plot a curve of force versus current for relay opening for the 3/4" and the 1-3/4" spring. Plot a curve of force versus current for relay closure for the 3/4" spring. Plot a curve of the energy stored versus spring deflection.

PROBLEMS

1. For the relay in figure 8-6, determine the source voltage required to cause the relay to pull-in. The relay coil measures 8k ohms and requires 5 mA for pull-in.

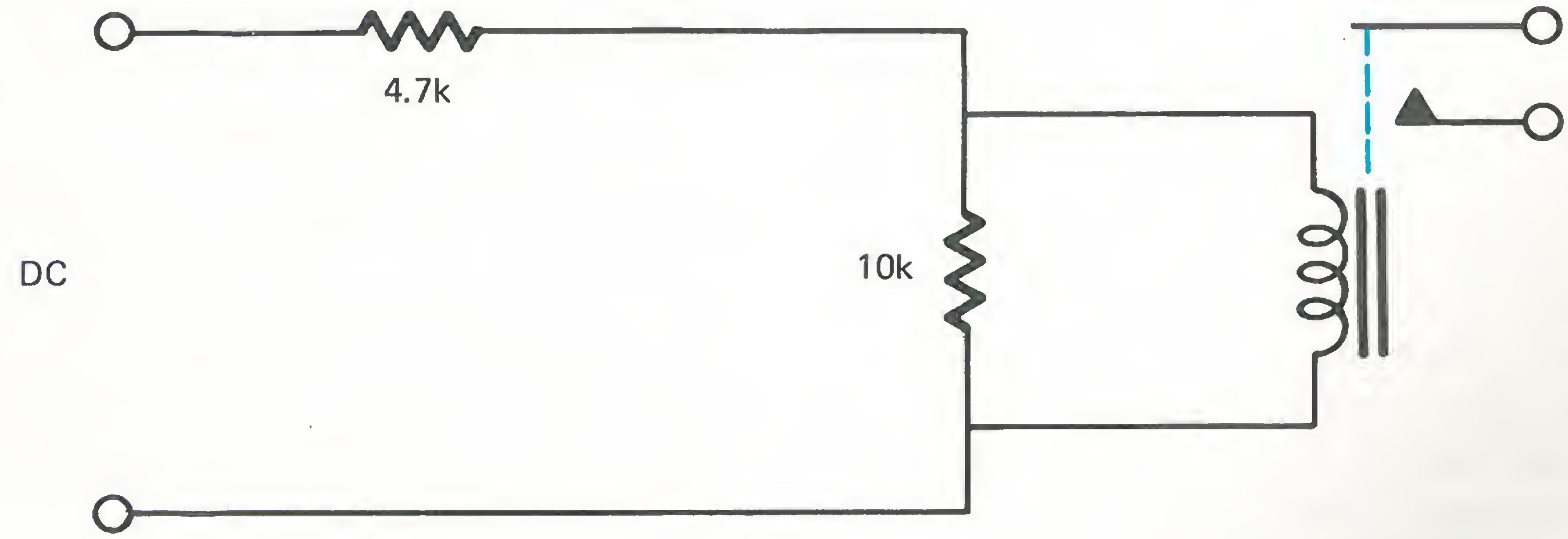


Fig. 8-6 Circuit For Problem 1

2. Using the library, find out how much the relays used in this experiment cost. If you cannot find the exact relay, determine the cost of a replacement as closely like the one used as possible. Include the detailed specifications found in the catalog.
3. If there are severe fluctuations in the coil voltage of a relay there would be the possibility of the relay dropping out. What type relay would you use to prevent this possibility? Discuss in detail how it works.
4. One type of relay used when extremely rapid switching is required (speeds within several microseconds are possible) is the "magnetic-reed" relay. Explain how this type relay operates.

experiment 9 ENERGY STORAGE IN A GENERATOR

INTRODUCTION. If the mechanical power to a generator is interrupted, the generator will continue to deliver energy to its load for a given interval of time. In this experiment, the dynamic storage of energy in a generator will be investigated.

DISCUSSION. A *generator* is a device that converts mechanical energy into electrical energy. A *prime mover,* a gasoline engine or steam turbine, is coupled through gears, belts or chains to drive the generator. Since the prime mover supplies the mechanical energy, it must do a given *amount of work* in driving the generator from the stopped position to the normal operating speed. After the generator reaches operating speed, the mechanical power supplied by the prime movers decreases to an amount that is equal to the energy required by the load plus any system losses. The losses in the generator system are due to the friction of the bearings, gears, etc.

If the mechanical power delivered by the prime mover is reduced, a portion of the *dynamic energy stored* in the generator will be returned to the system. This energy will tend to cause the output of the generator to remain at the original value. If the mechanical power delivered by the prime mover is increased, an increase in work must be done on the system in storing the additional energy in the generator.

The dynamic energy stored in the generator is stored in the *rotating mass* by virtue of its angular velocity. The ability of a rotating mass to store or deliver energy is a property known as *inertia.* The kinetic energy stored in a rotating mass due to inertia may be determined by

$$KE = 1/2\, I\, \omega^2 \qquad (9.1)$$

From equation 9.1, the energy stored is proportional to the inertia, I, in slug-ft.^{2}, and to the angular velocity, ω, in radians per second. The inertia of a rotating solid cylinder is

$$\boxed{I = 1/2\, mr^2} \qquad (9.2)$$

An example of the effect of inertia is illustrated in figure 9-1. With switches S_1 and S_2 closed, the motor will drive the flywheel to a given speed. The speed of the flywheel is proportional to the *power,* P, in lb.-ft./sec. delivered by the motor and inversely proportional to the *torque,* T, in lb.-ft., required by the flywheel. The speed may be calculated by

$$\omega = P/T \qquad (9.3)$$

The angular velocity in radian/sec. may be converted to revolutions per minute by

$$\omega = \frac{60\,\omega}{2\pi} \text{RPM} \qquad (9.4)$$

If the switch S-2 is opened, de-energizing the friction clutch, the flywheel will continue to rotate for a given amount of time. During this interval of time, the flywheel obtains its ability to do work from the kinetic stored energy. The inertia of a disk-shaped flywheel can be determined by

$$I = 1/2\, mr^2$$

If w = weight of flywheel
g = acceleration of gravity, 32 ft./sec.^{2}
r = radius

then we have

$$I = 1/2 \left(\frac{w}{g}\right) r^2 \qquad (9.5)$$

Therefore, the energy stored in the flywheel the instant the friction clutch is de-energized may be calculated by equation 9.1.

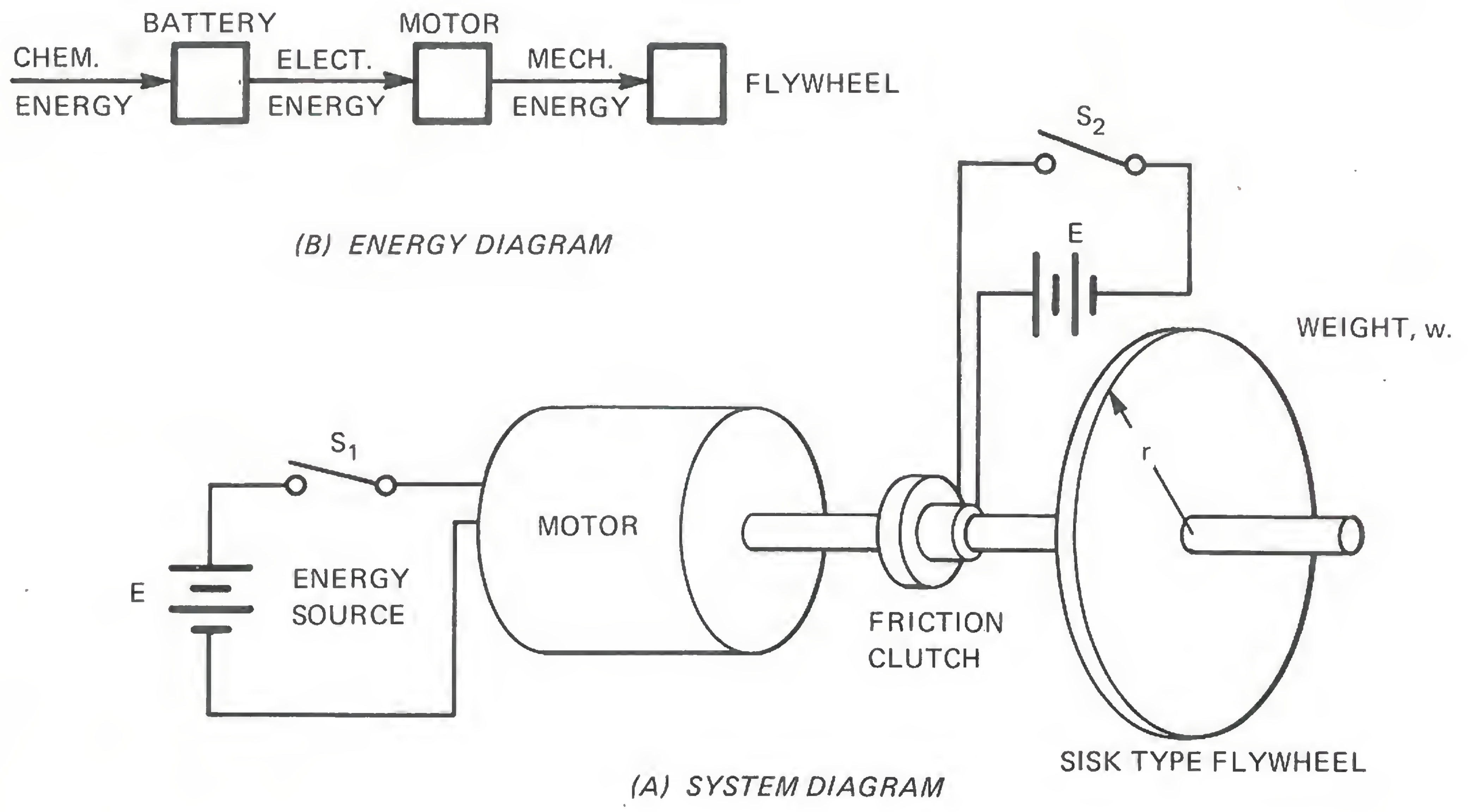


Fig. 9-1 Flywheel System

The basic AC and DC generator depend upon the principle that when a conductor is passed through a *magnetic field* a current is generated. A simple generator is shown in figure 9-2. The generator consists of a one-turn *armature,* a *permanent magnet field* and a method of removing the current from the armature winding. The method of removing the current in an AC generator is accomplished with *slip rings* and *brushes.*

In a DC generator the voltage is *rectified* by the action of the *commutator* and is brought out through brushes. The amount of voltage, e, induced into the armature depends on the number of turns, N, the amount of magnetic flux, the rate at which the conductor is moving through the field, $\frac{\Delta\theta}{\Delta t}$, and the angle of conductor with respect to the magnetic field. This relationship may

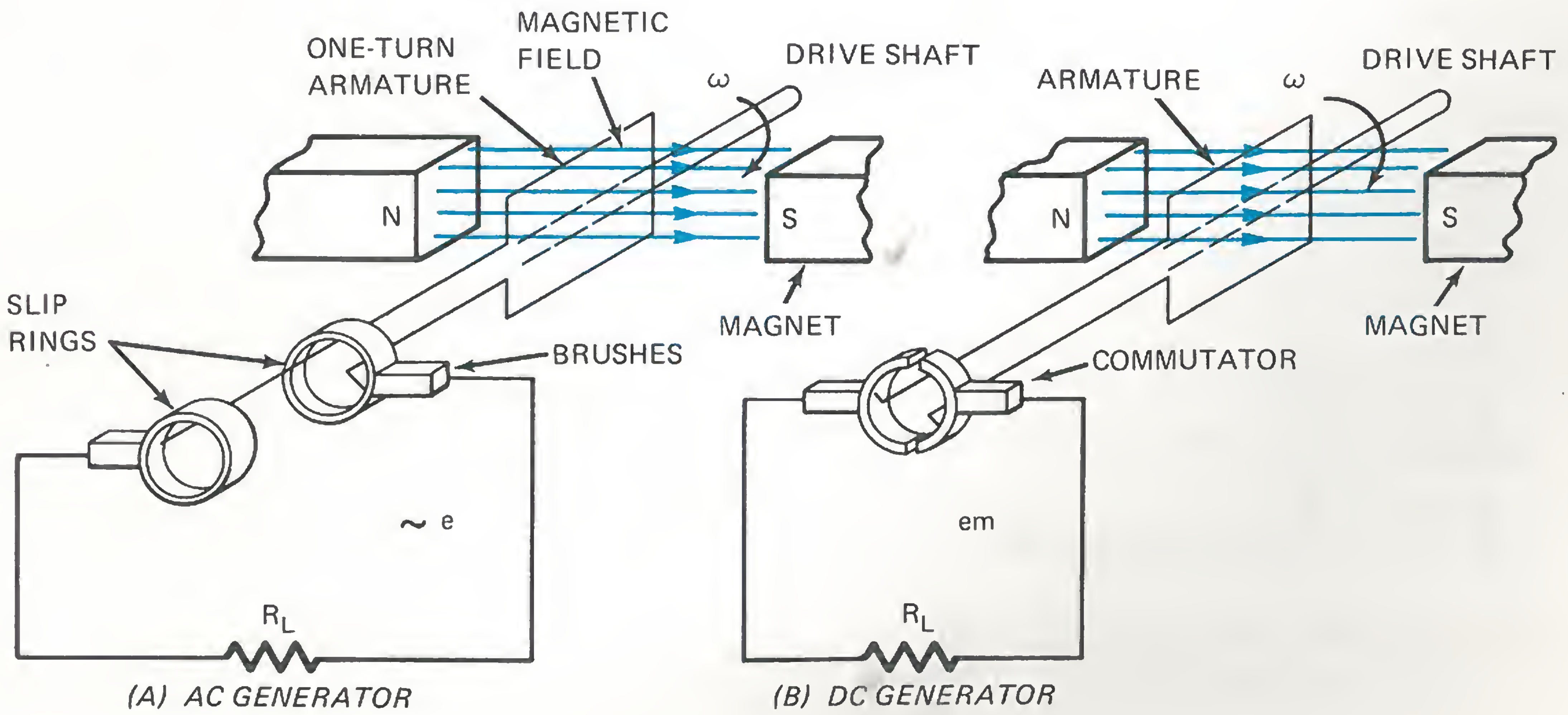


Fig. 9-2 One-Turn Generator

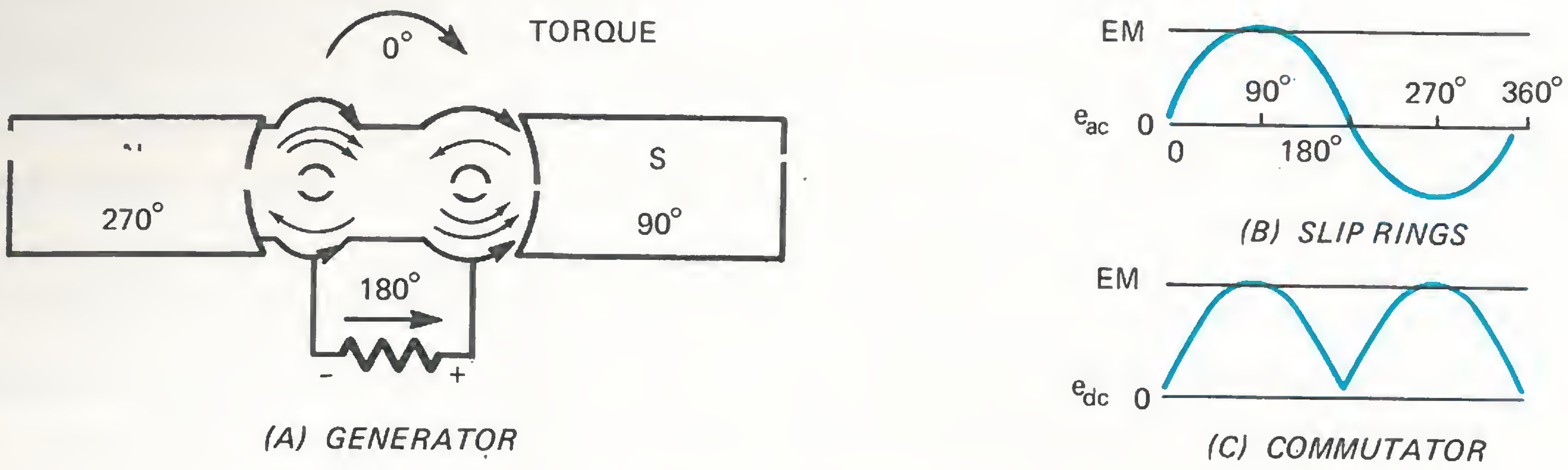


Fig. 9-3 Voltage Generation

be expressed as

$$e = N \frac{\Delta\theta}{\Delta t} \tag{9.6}$$

When the armature is rotated through a magnetic field at a constant angular velocity, the *instantaneous voltage* induced into the armature is a function of the flux lines at each angle. An inspection of the generator system shown in figure 9-3 reveals that the maximum flux is cut at 90° and 270°; therefore, the maximum induced voltage will occur at these angles. At 0° and 180°, the conductors are moving parallel to the magnetic lines of force and the induced voltage is zero. The voltage and wave forms that are generated are shown in figure 9-3b and c.

To determine the direction of current, use the *lefthand rule.* Place the index finger of the left hand in the direction of the flux produced by the current flowing in the coil as shown in figure 9-4. The thumb will point in the direction of the electron flow. To determine the direction of the flux, recall that for every action there is a reaction: therefore, knowing the direction of rotation of the armature, the reaction is in the opposite direction. The flux lines are like rubber bands, they represent a *tension,* which tends to make them as short as possible. The net force produced by the magnetic lines of force is in the same direction as the reaction. Magnetic lines of force traveling in the same direction have the effect of adding their net forces. Magnetic lines of force traveling in the opposite direction have the effect of their net forces cancelling to produce the proper reaction torque. The magnetic flux about coil A is CCW, while the flux about coil B is CW. The current producing this flux must flow into coil A and out of coil B.

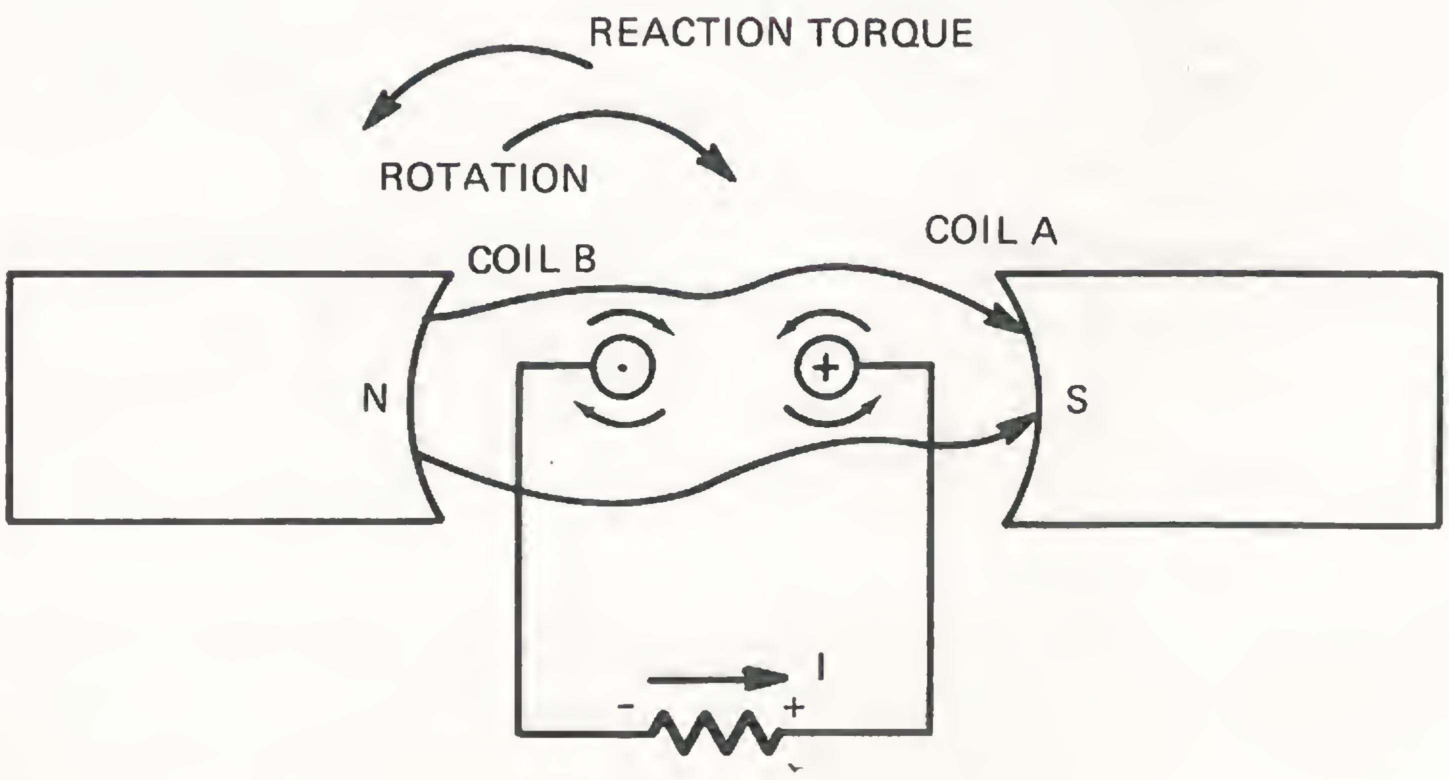


Fig. 9-4 Current Produced by Generator Action

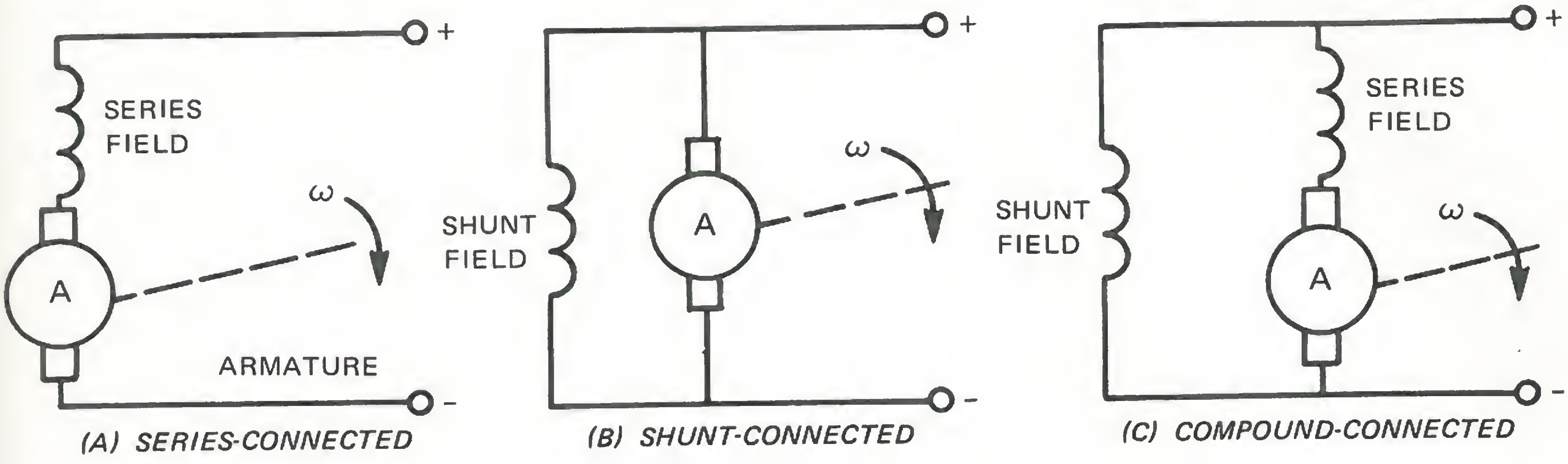


Fig. 9-5 Self-Excited Generators

Except for DC generators whose output power is small, the magnetic field required for generator action is produced by an electromagnet. The field is produced by passing current through a conductor wound on a pole piece. Generators are usually classified by the manner in which their field windings are connected. The generator may be self-excited or separately excited. The self-excited generator produces the current for the field, while the separately excited generator obtains its field current from an external source. Figure 9-5 shows the three basic configurations of self-excited DC generators. In self-excited generators, the field must contain *residual magnetism* or the generator will not produce an output.

Generators designed to supply AC current are called *alternators.* The rotating field in an alternator is called the rotor. The armature windings are stationary in alternators and are called the stator. Alternators require a DC current for their fields. The DC current is termed the excitation current. The excitation voltage for the field is sometimes supplied by a DC generator called an *exciter*. The exciter may be mounted directly on the rotor shaft of the alternator.

Alternators are classified by the type stator used. The generator may be classified as a *single-phase, two-phase* or a *three-phase* system. The three-phase generator is the most popular because it is the most efficient. The three-phase generator may contain a delta- or wye-wound armature, figure 9-6.

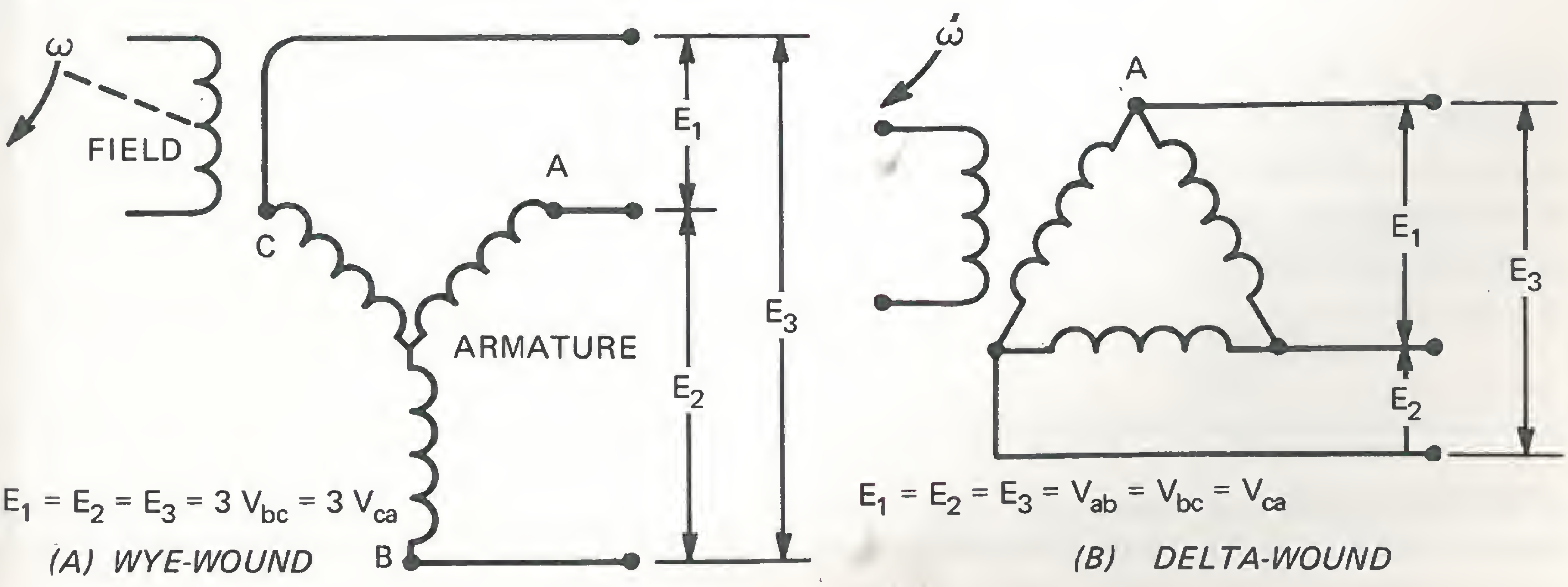


Fig. 9-6 Three-Phase Alternator

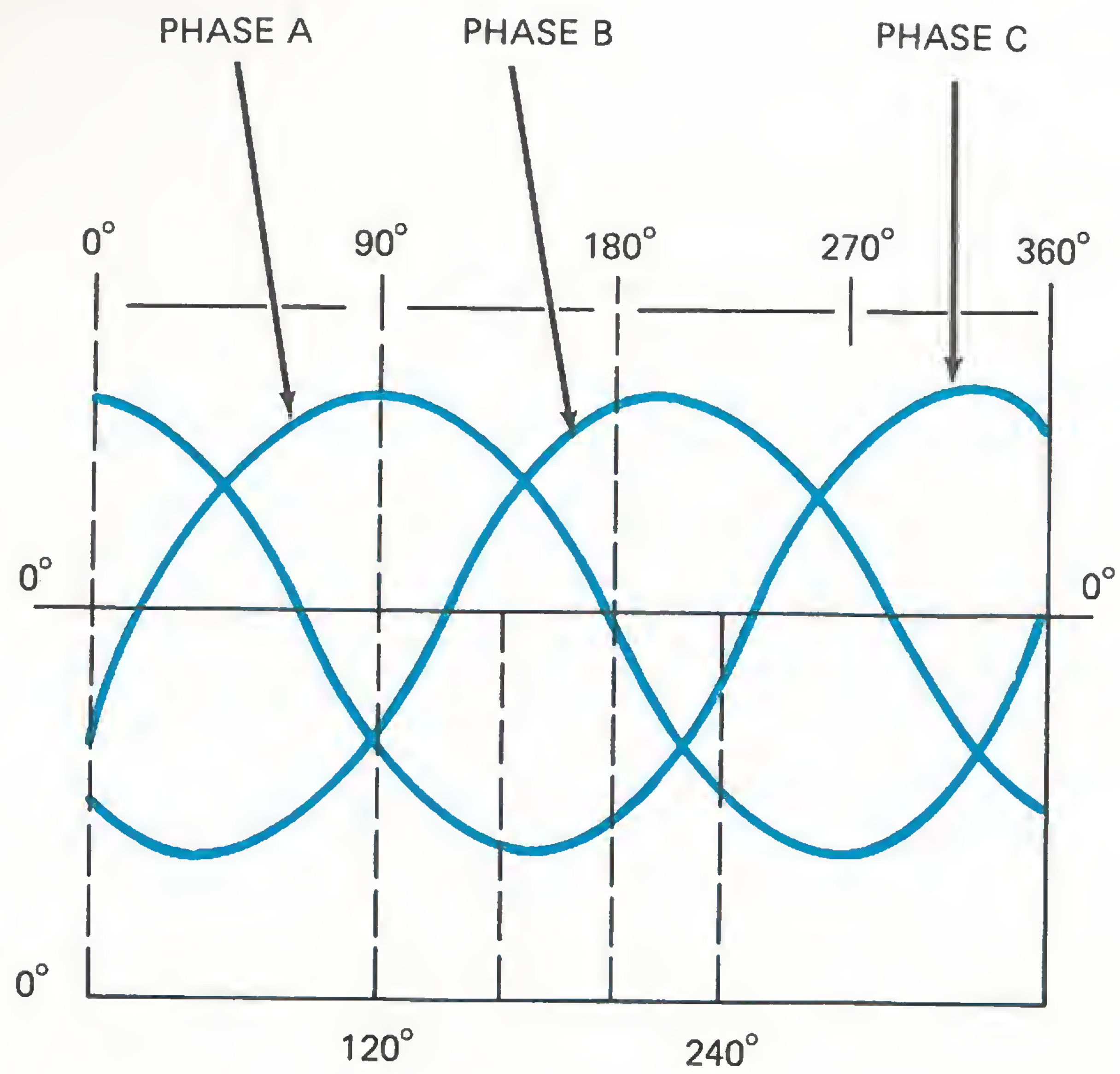


Fig. 9-7 Three-Phase Alternator Output

The three-phase alternator has three output voltages. The voltages are at an angle of 120° with respect to each other. This angle is referred to as the *phase angle.* The output of the three-phase generator is shown in figure 9-7.

The voltage generated by a generator with multiturns is

$$e = \frac{\phi \, \overline{P} \, (RPS) \, Z}{p \, 10^8} \qquad (9.7)$$

where ϕ is the flux in maxwells, $\overline{P}$ is the number of poles, Z is the number of conductors, p is the number of paths and RPS is the revolutions per second. The frequency of the output voltage is

$$f = \frac{\overline{P} \, (RPS)}{7200} \qquad (9.8)$$

The electrical equivalent circuit of a simple generator is shown in figure 9-8. R_{int} is the internal resistance of the generator armature and E is the generated voltage. The generated voltage can be determined by equation 9.7.

The efficiency of the generator may be found by

$$\% \text{ Eff.} = \frac{p_o}{p_{in}} \times 100 \qquad (9.9)$$

It should be noted that the output power is electrical and the input power is mechanical. Therefore, the mechanical or the electrical power must be converted to like units.

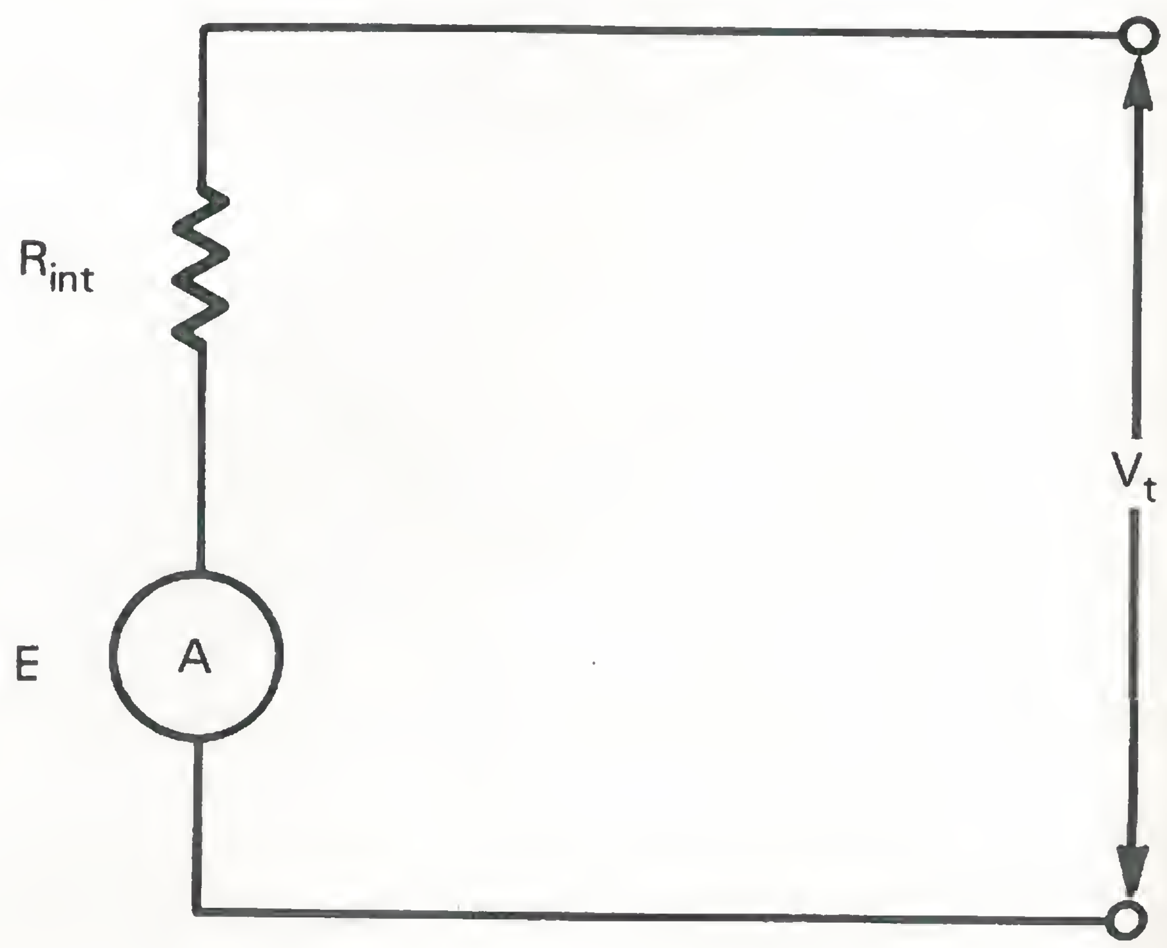


Fig. 9-8 Equivalent Circuit.

MATERIALS

1 Motor, DC 28 volts, 1/100 hp 7000 RPM

1 Generator, 3.8 volts/100 RPM

1 Supply, 0-28 volts DC

1 Recorder, strip chart

1 Resistor, 5 k , 2 watts

1 Resistor, 5 ohm, 20 watts

1 VOM

1 Switch, SPST

1 Coupling, generator shaft to motor shaft

1 Breadboard with legs

PROCEDURE

1. Construct the experimental circuit shown in figure 9-9.

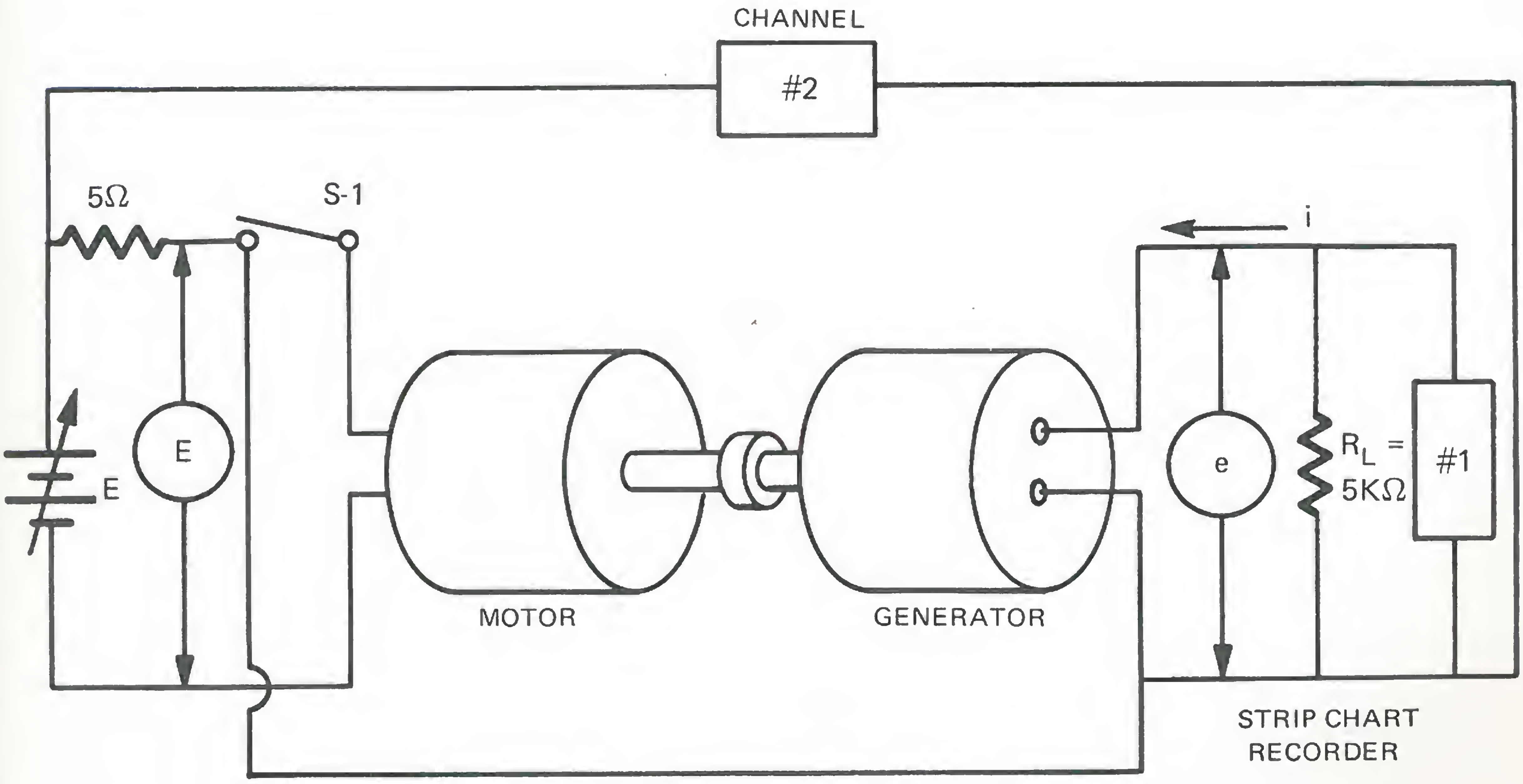


Fig. 9-9 Experimental Test Circuit

2. Adjust the applied voltage, E, until the motor speed is constant at 1500 RPM.
3. Using a VOM, read and record the applied voltage in the data table (figure 9-10) as E.
4. Using a VOM, read and record the voltage across the load resistor, RL, in the data table as e.
5. Adjust the voltage/mm of the strip chart recorder to a convenient setting and record the setting in the data table as V/mm.
6. Adjust the speed, mm/sec., of the strip chart recorder to a convenient setting and record the setting in the data table as mm/s.
7. Open switch S-1.

S = 1500 RPM

E	e	V/mm	mm/s	t	i	p

S = 2500 RPM

E	e	V/mm	mm/s	t	i	p

S = 3500 RPM

E	e	V/mm	mm/s	t	i	p

Fig. 9-10 The Data Tables

8. From the strip chart recorder trace, calculate the voltage, e,

$$e = V/mm\ (mm\ of\ deflection)$$

for various points on the trace. Record these data in the data table as e.

9. From the strip chart recorder trace, calculate the time, t,

$$t = (mm\ of\ deflection)\ /\ mm/sec.$$

for the same voltage points recorded in step 8. Record these data in the data table as t in sec.

10. Calculate the instantaneous load current at each of the voltage points recorded in step 8. Record these data in the data table as i.

11. Calculate the power at each of the voltage points recorded in step 8. Record these data in the data table as p.

12. Repeat steps 3 through 11 for a motor speed of 2500 RPM and 3500 RPM.

ANALYSIS GUIDE. Plot a graph of load voltage versus time (from switch S-1 opening). Plot a graph of load current versus time. Plot a graph of load power versus time. Determine the energy stored in the system at the instant the switch is opened (the energy is the area under the power curve).

PROBLEMS

1. A plastic hoop has a radius of 2 ft. and weighs 8 ounces. Calculate its moment of inertia.

2. Calculate the dynamic energy stored in the hoop of problem 1, if its angular velocity is 100 RPM.

3. An automobile engine exerts a torque of 250 lb-ft at 400 RPM on its crankshaft. Calculate the horsepower developed by the engine.

4. The tire of a boat trailer is 18 inches in diameter. If the tire is rotating at 1500 RPM, what is its angular velocity and what is the linear speed of a point on the tread?

5. A 10-lb. cylinder with a radius of 6 inches rolls down a loading ramp 15-ft. long that is at an angle of 30° to the horizontal. Determine the cylinder's angular velocity and linear velocity at the bottom of the ramp. What is the static energy stored in the cylinder before it moves down the plane? What is the rotational energy and the translational energy of the cylinder at the bottom of the ramp?

experiment 10 RELAY TIME CONSTANTS

INTRODUCTION. A relay is basically an electromagnetic switch that is operated by a variation in one electric circuit and that changes the operation of other devices in the same or in other electric circuits. In this experiment we will investigate the amount of time that it takes the relay contacts to open and close when energized by a source.

DISCUSSION. A relay is a relatively simple magnetic device which is normally made of a coil, a core, and a movable armature. A set of making and breaking contacts is located on the movable armature. Figure 10-1 shows a basic relay.

When current flows in the coil, the core is magnetized and lines of force are developed in the core and through the armature and the body of the relay. The air gap between the core and the armature is filled with magnetic loops trying to contract. When the contracting lines of force become great enough to overcome the tension of the spring, the armature will be pulled toward the core, closing the relay contacts. When the current in the coil is removed, the magnetic circuit loses its magnetism and the spring pulls the armature up, opening the contacts.

The length of the air gap between the armature and the core can be varied by adjusting the stop on the armature. The closer the armature is to the core, the greater the magnetic pull will be for the same number of ampere-turns and the current in the core will not have to be as great to pull the armature in. Decreasing the distance between the armature and the core also reduces the time it takes for the armature to travel from the rest position to the operating position. A closed path for the magnetic flux is provided by the core, the air gap, the armature and the frame. In order to secure maximum concentration of flux at the air gap, the three magnetic components are made of a *highly permeable* material such as soft iron.

Relays are useful in remote closing and opening of high-voltage or high-current

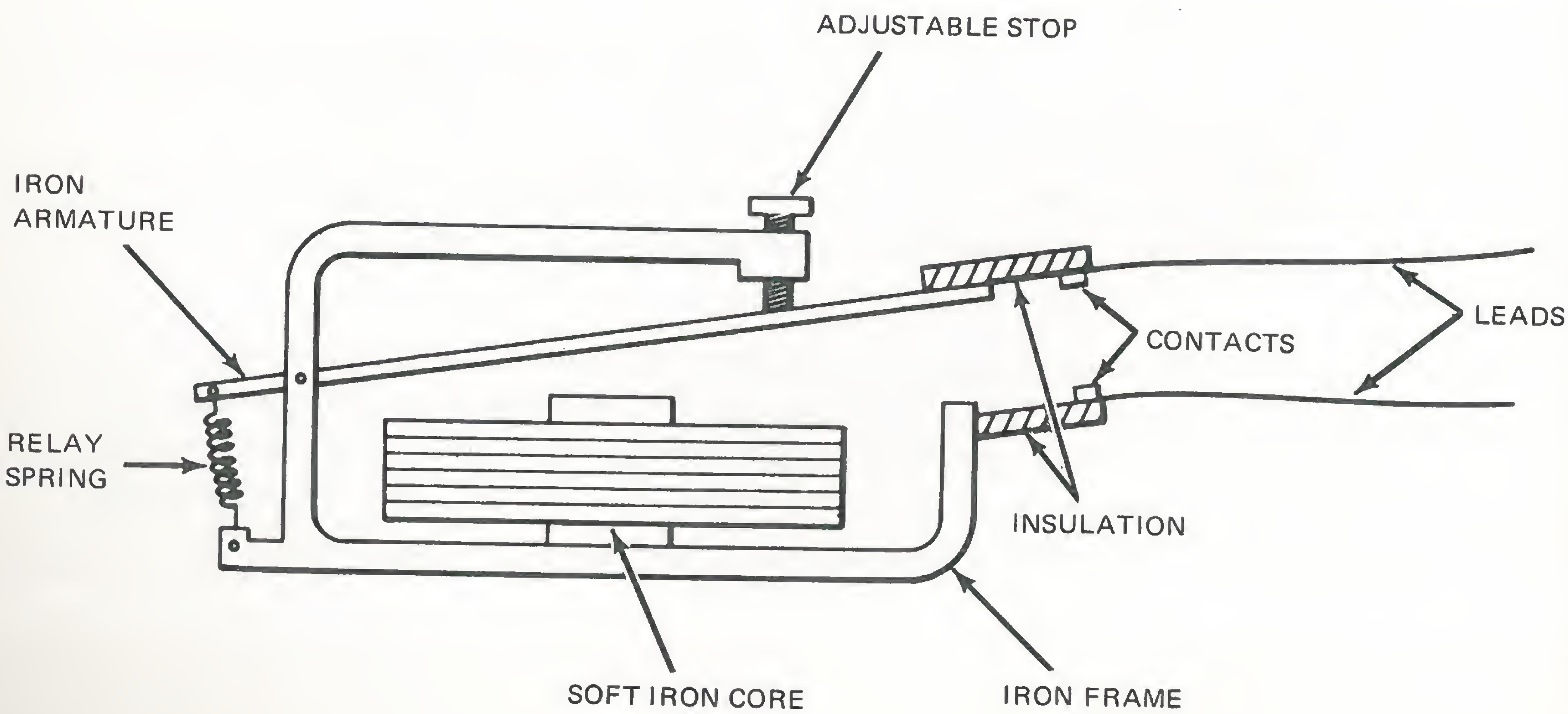


Fig. 10-1 Basic Relay

circuits with relatively little voltage or current flowing in the coil. Relay contact notation is usually given in the following order: (1) *poles,* (2) *throws,* (3) and *normal position.* The pole designation gives the number of movable contacts in the relay. Relays are available that have as many as 100 movable poles. The throw designation designates the number of stationary contacts available on the relay. If there are two stationary contacts, there can be one independent circuit operating off of each. The movable contact will either be energizing one circuit with the other one unenergized or vice versa. Figure 10-2 shows the difference in the single- and double-throw contact arrangements.

The contacts in a relay may be arranged to open or close in a number of different ways. A combination of a stationary contact and a movable contact that is disengaged when the coil is unenergized is referred to as being *normally open,* abbreviated NO. A combination of a stationary contact and a movable contact that is engaged when the coil is unenergized is known as being *normally closed,* NC.

A single-pole single-throw relay with the contacts normally open is abbreviated SPSTNO. A single-pole single-throw relay with the contacts normally closed is abbreviated SPSTNC. The nomenclature adopted for these two relays for basic circuits is shown in figure 10-3.

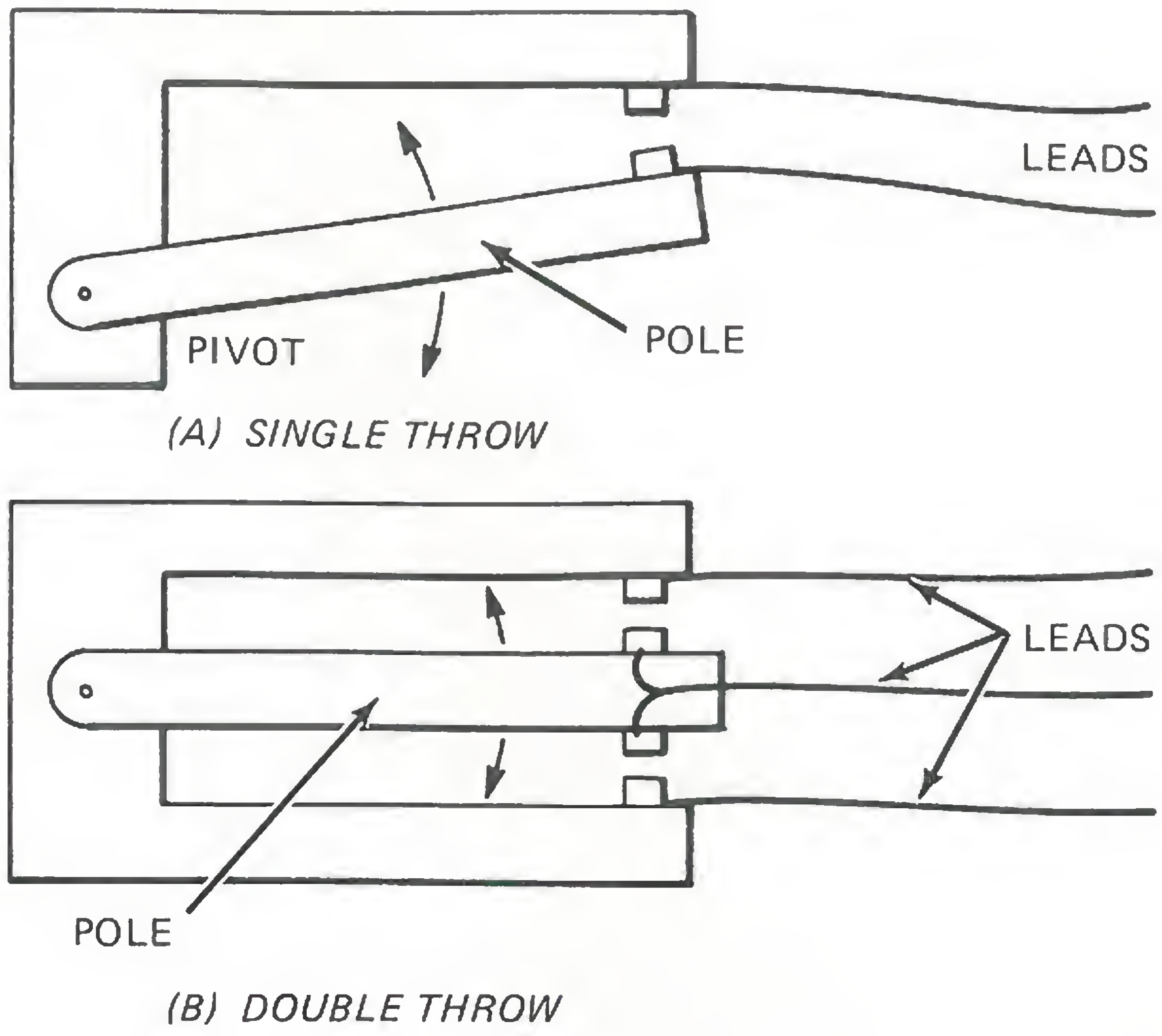


Fig. 10-2 Single and Double Throw Relay

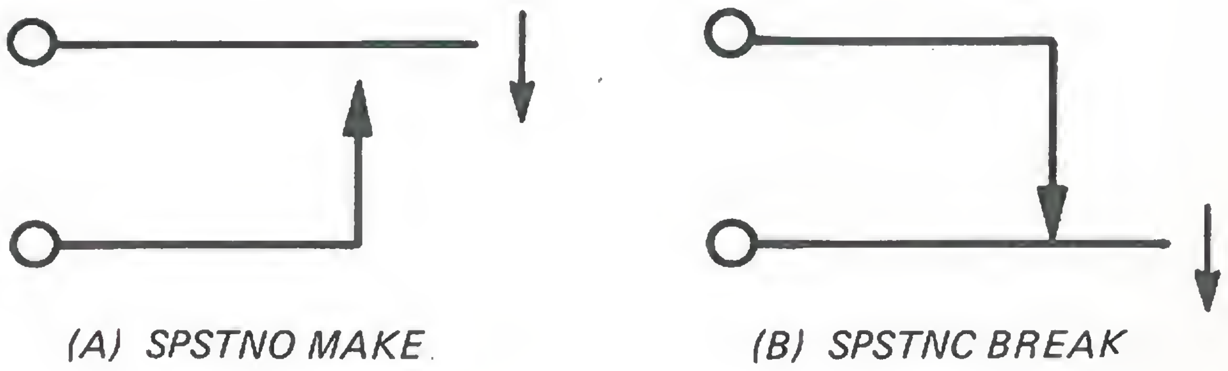


Fig. 10-3 Make and Break Relay Nomenclature

A double-throw contact may be classified as either a make-break or a break-make contact relay. In the make-break arrangement shown in figure 10-4a, the normally open contacts must make before the normally closed contacts break. In the break-make arrangement shown in figure 10-4b, the normally closed contacts must break before the normally open contacts close. There are

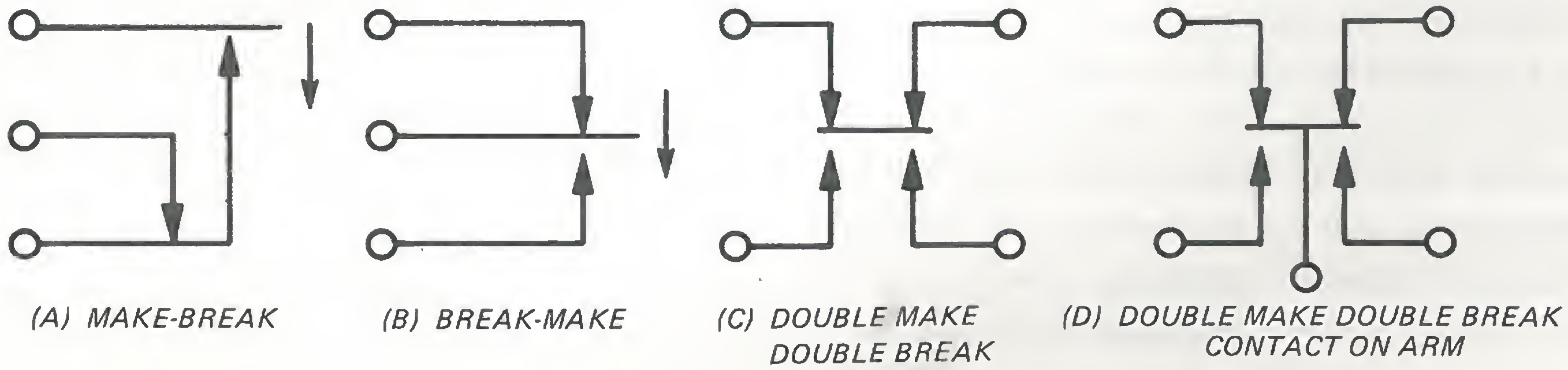


Fig. 10-4 Basic Relay Circuit Nomenclature

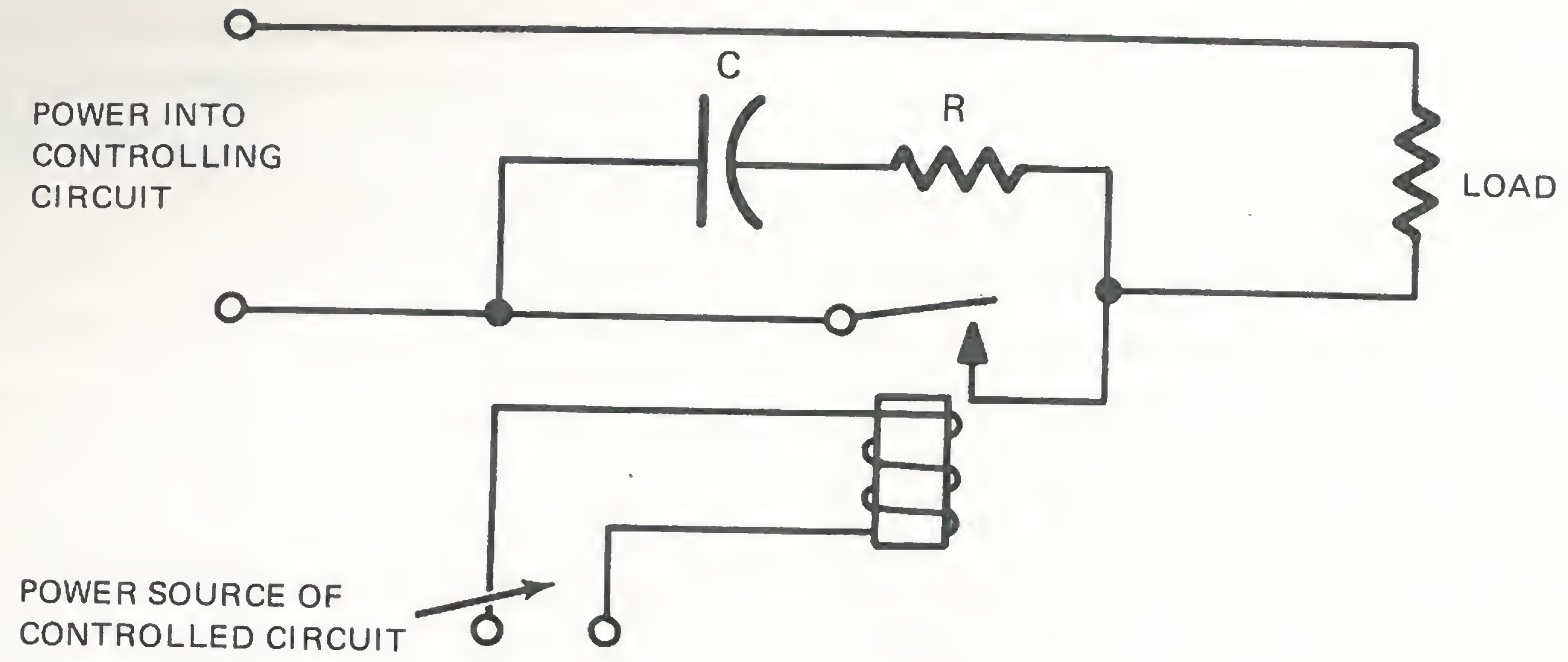


Fig. 10-5 Resistance – Capacitance Filter Circuit

other variations of these two contact arrangements usually referred to as double-break, DB, and double-make, DM, contacts. Figure 10-4 shows a few of the more common relay circuits.

Relay contacts are usually made of silver or tungsten. To make good contact between the relay contacts, the *oxides* produced on the silver should be cleaned by using a very fine abrasive paper rubbed between the contacts. If the contacts are pitted by heavy currents, they may be smoothed with a fine file, but care should be used when doing this so that the contacts will retain their original shape to allow the normal wiping action during closing to keep them clean.

The pitting that is formed on the contacts results from the arc that forms between them when they are separated. As the contacts move farther apart, the arc will stretch out and finally break. The spacing at which the arc is extinguished is determined by the load current and the source voltage. It should be apparent that the contacts must be allowed to move far enough apart to extinguish the arc. There have been means devised which aid in minimizing the amount of arcing between contacts. One method which will be briefly discussed is known as a *resistance-capacitance filter circuit.* This circuit is shown in figure 10-5.

When the relay is not energized, the contacts will be open and the load will be inoperative. The capacitor will be charged to the value of the voltage in the controlled circuit. When the relay is energized and the contacts closed, the load will become operative. The voltage of the capacitor will discharge through the resistor and the relay contacts. When the relay opens again, the contacts become short-circuited by the uncharged capacitor and the resistor, and the arc formation will be prevented. As the capacitor charges, the voltage across the contacts increases. However, when the voltage across the contacts reaches an amount great enough to cause an arc, the contacts will have opened far enough to prevent the formation of an arc.

As the previous discussion indicates, there is some time involved from the first energizing of the relay circuit to the point when it is completely operating. This time lag depends on various things in the relay, and is commonly called the *time constant* of the relay. The electrical time constant depends upon the resistance and the inductance of the coil windings. The electrical time constant of the relay coil is defined as

$$\boxed{\tau_{elect} = L/R}$$

where τ = time constant, R = resistance of the coil, L = inductance of the coil.

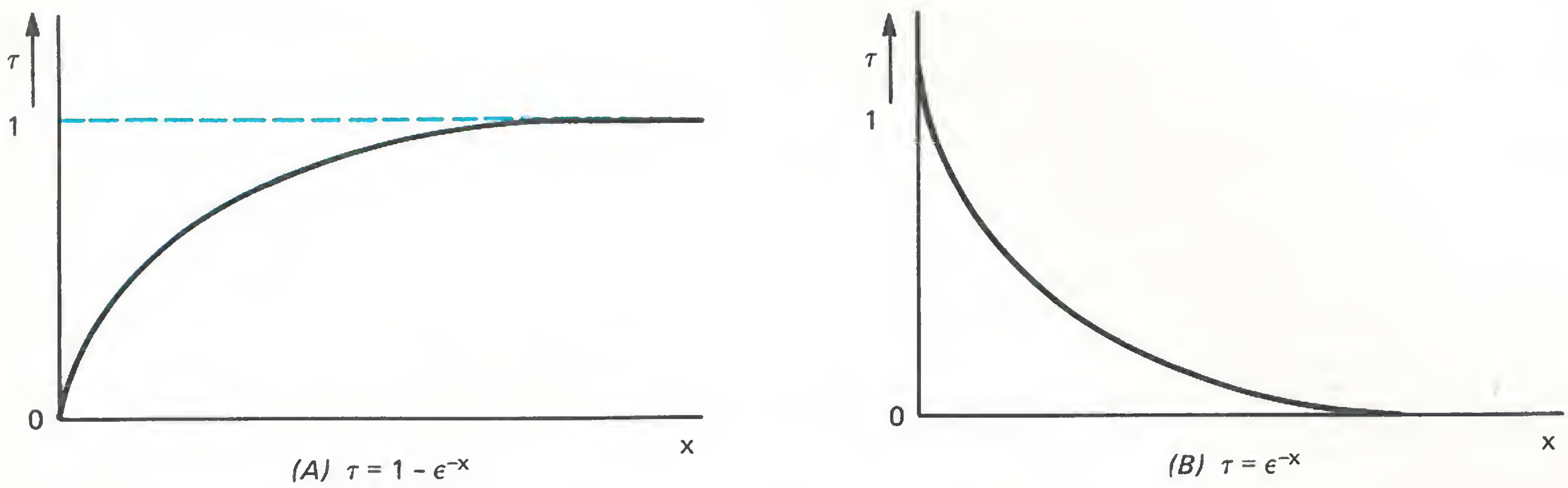


Fig. 10-6 Graphs of Exponential Curves Used with Time Constants.

The mechanical time constant depends upon the mass of the moving armature, the friction of the armature against the bearing surfaces and the spring stiffness involved which must be overcome.

A third time constant might involve heating effects. This time constant is known as a thermal time constant.

In this experiment the electrical time constant will be investigated as well as the time delay of the movable pole in going from one contact to the other. But before getting into time constants, a brief look at graphing exponentials is in order.

Two common exponentials used when working with time constants are ϵ^{-X} and $1\text{-}\epsilon^{-X}$. These two curves are graphed in figure 10-6.

Evaluating equation (a) in figure 10-6 would show that as x increases, ϵ^{-X} would become very small. When a very small number is subtracted from 1, the results, τ, will approach one. Notice that the curve never reaches one but only approaches it. To evaluate equation (b) in figure 10-6, one would see that as x increases, ϵ^{-X} becomes very small. Therefore, τ begins at one when x is zero and approaches, but never reaches, zero as x increases.

These two curves represent the equations that are formulated when dealing with time constants. The equations themselves are formulated with the use of differential equations and will not be discussed as to their derivation. However, a simple RC circuit will be looked at and the voltage curves will be plotted so that a time constant will be better understood.

Figure 10-7 shows a simple RC circuit. It will be assumed that the capacitor is not charged at t = 0.

Because of the capacitor's characteristics, it acts as a short circuit when it is first energized. As time increases, the voltage across it increases until it reaches some maximum value, usually the value of the source input. When it is fully charged, it acts in much the same way as an open circuit, and allows no electron flow in its circuit.

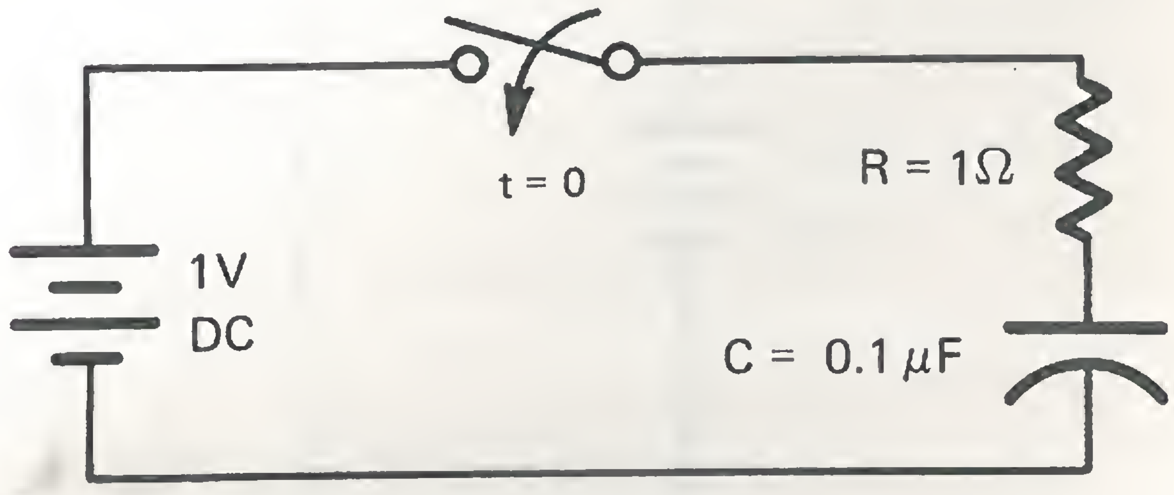


Fig. 10-7 The Basic RC Circuit

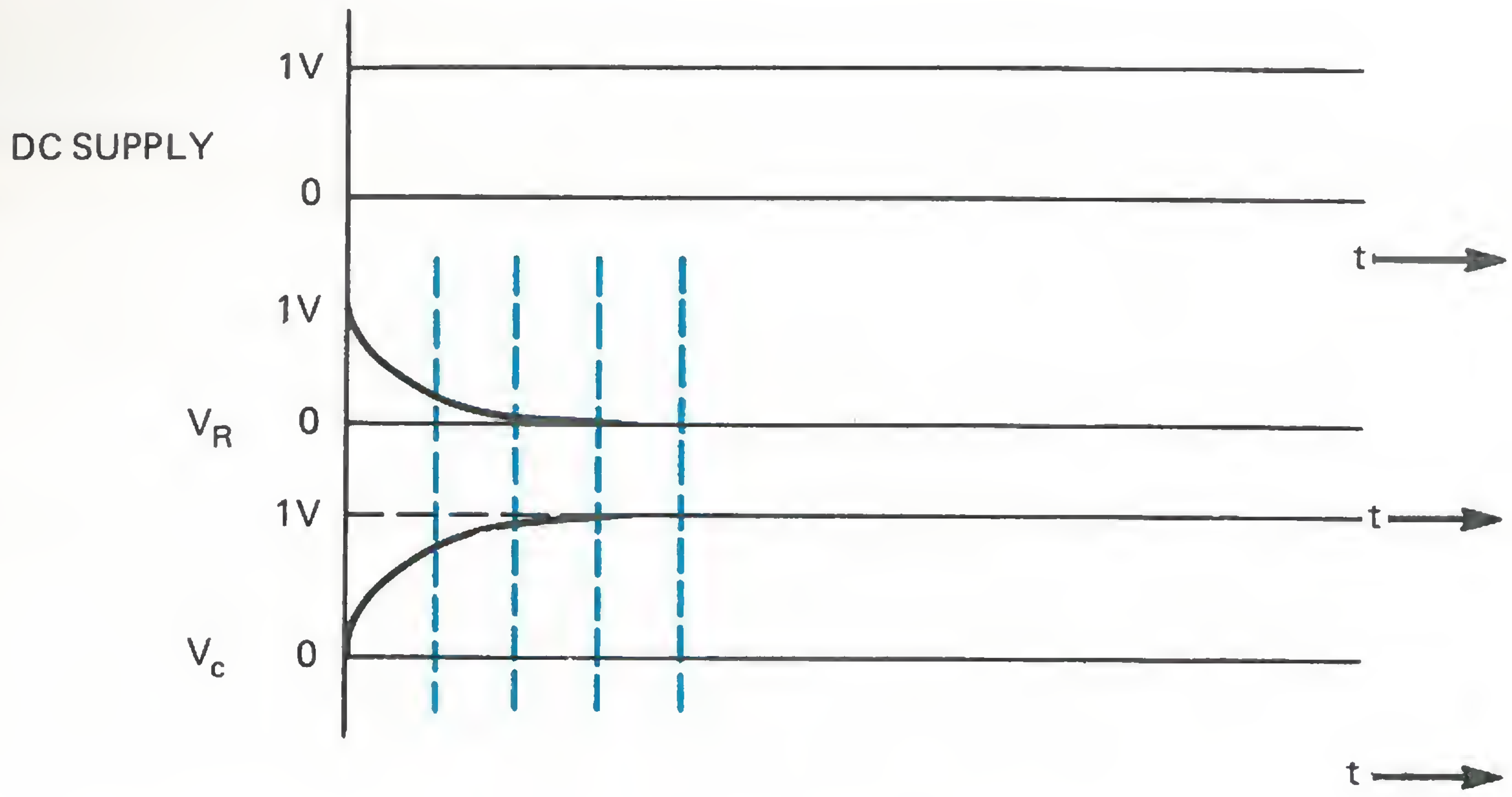


Fig. 10-8 Waveforms From Circuit In Figure 10-7

In the circuit in figure 10-7, the capacitor acts as a short circuit when the switch is first closed at t = 0. The current from the battery flows through the resistor and the corresponding voltage drop across the resistor should equal, by *Kirchhoff's Voltage Law*, one volt. However, this is only momentary because as time increases, the voltage appearing across the capacitor increases, the current through the circuit decreases, and the voltage across the resistor decreases. These things happen in accordance with the curves shown in figure 10-6 and are graphed to look like the ones in figure 10-8. The waveforms are graphed in time sequence to help eliminate any error that might be encountered.

It should be noticed that the waveforms of V_R and the voltage V_c could be added to equal the supply voltage of one volt for any time, t. This is what must happen because there are no other elements in the circuit. It is good practice to graph such waveforms in time sequence to provide an easy way of checking the results.

To evaluate the discharge path of a capacitor, the circuit in figure 10-9 will be used.

When the relay contact is at position 1 the capacitor will charge up toward one volt and the voltage waveforms will resemble the ones in figure 10-8. Suppose after a certain length of time the relay moves to position 2.

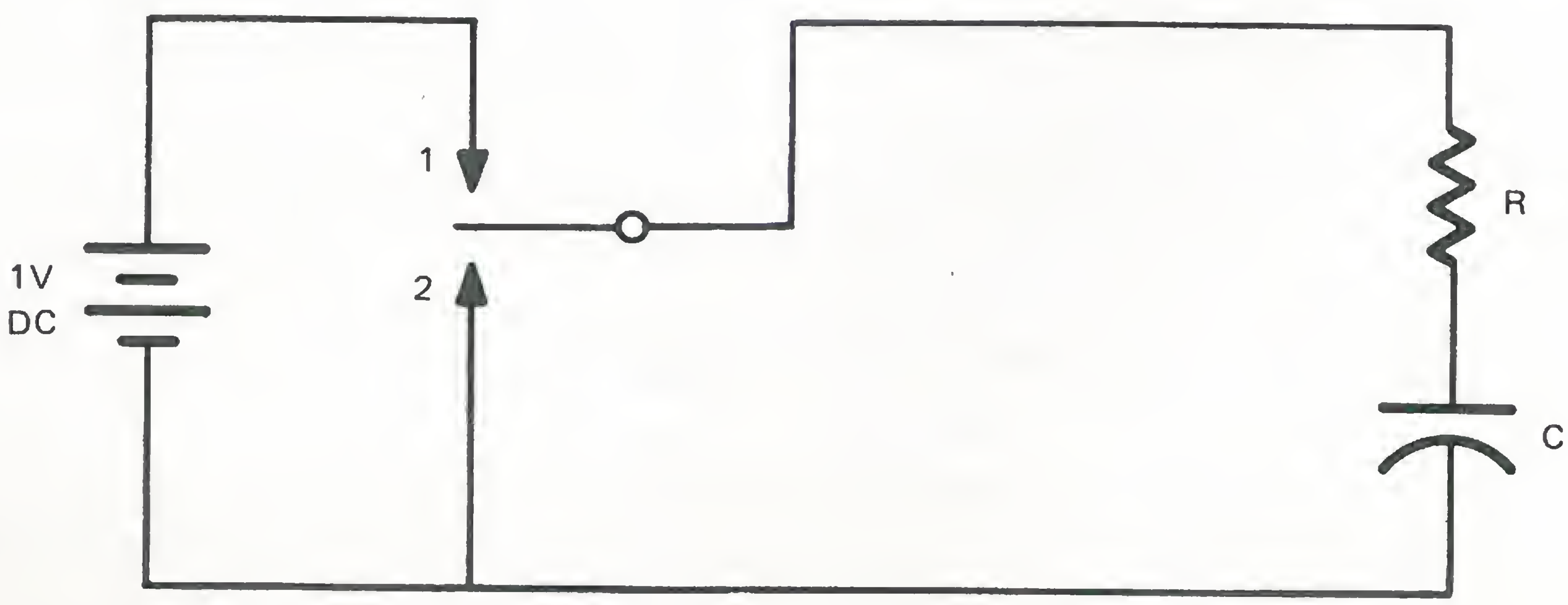


Fig. 10-9 Charge and Discharge Circuit For Capacitor

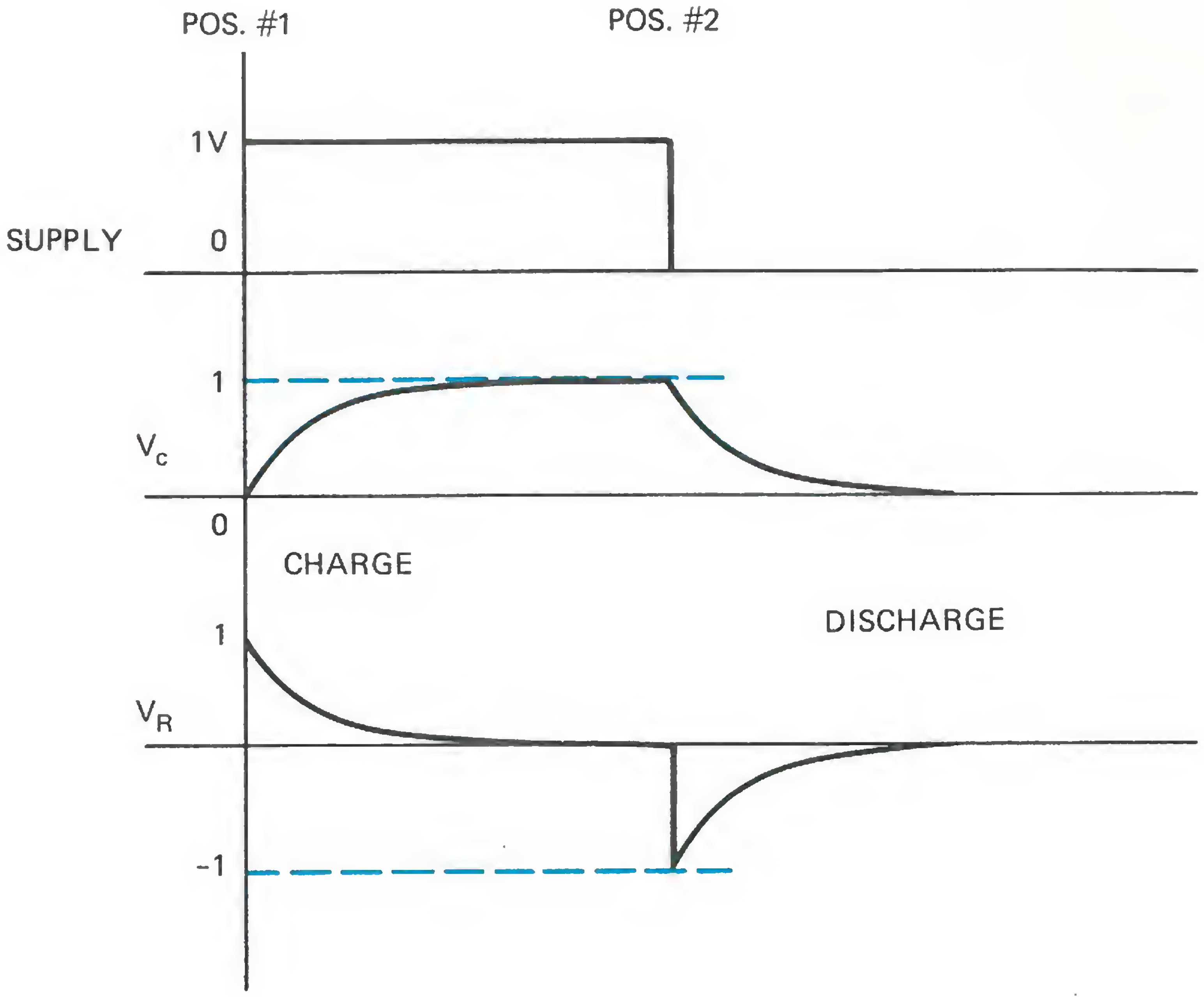


Fig. 10-10 Waveforms For the Circuit In Figure 10-9

With the battery switched out of the circuit, the capacitor will release its charge through the resistor and the relay contacts. The voltage will discharge at an exponential rate in the same manner that it charged up. Figure 10-10 shows the charging and discharging rates for the circuit in figure 10-9.

Notice that the waveforms for V_R and V_C will add together to equal the supply voltage at any time, t, just as in figure 10-8.

The discharge path of V_R is from the negative side because the current from the capacitor reverses direction in the resistor. The time constant, τ, of the RC circuit is what determines the rate of charging and discharging. The time constant is defined as the length of time in seconds that it will take the capacitor to charge to its steady state value *if* it were to continue to rise at its initial *rate-of-change* for the whole time interval. This is shown graphically in figure 10-11.

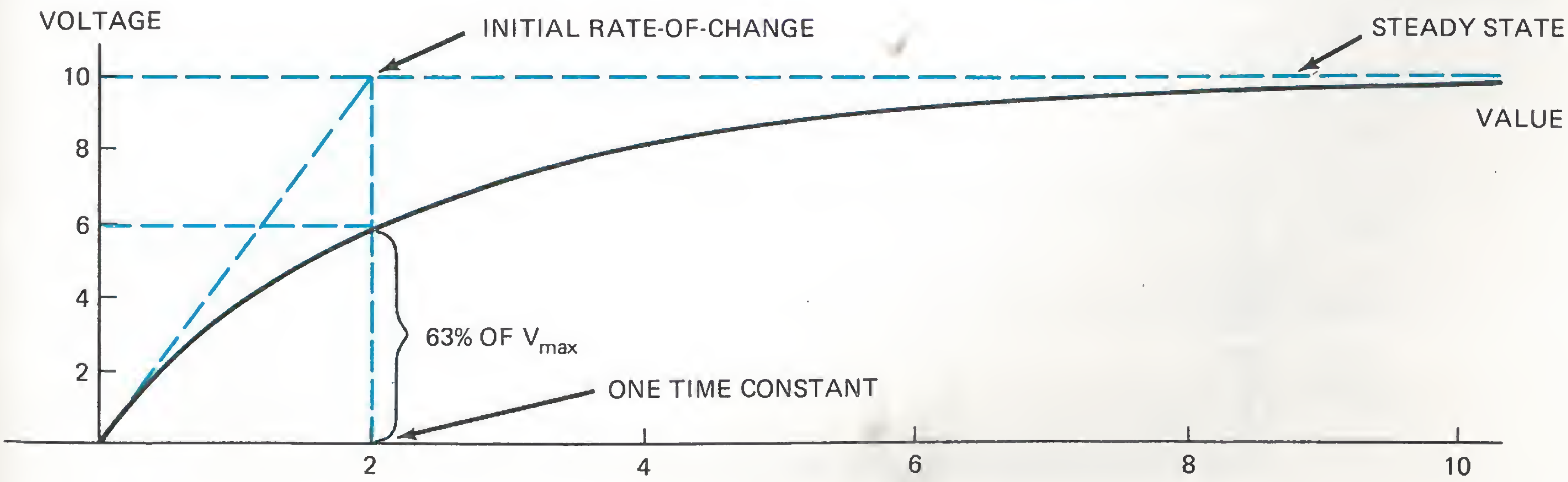


Fig. 10-11 Rise In Voltage Of an RC Circuit

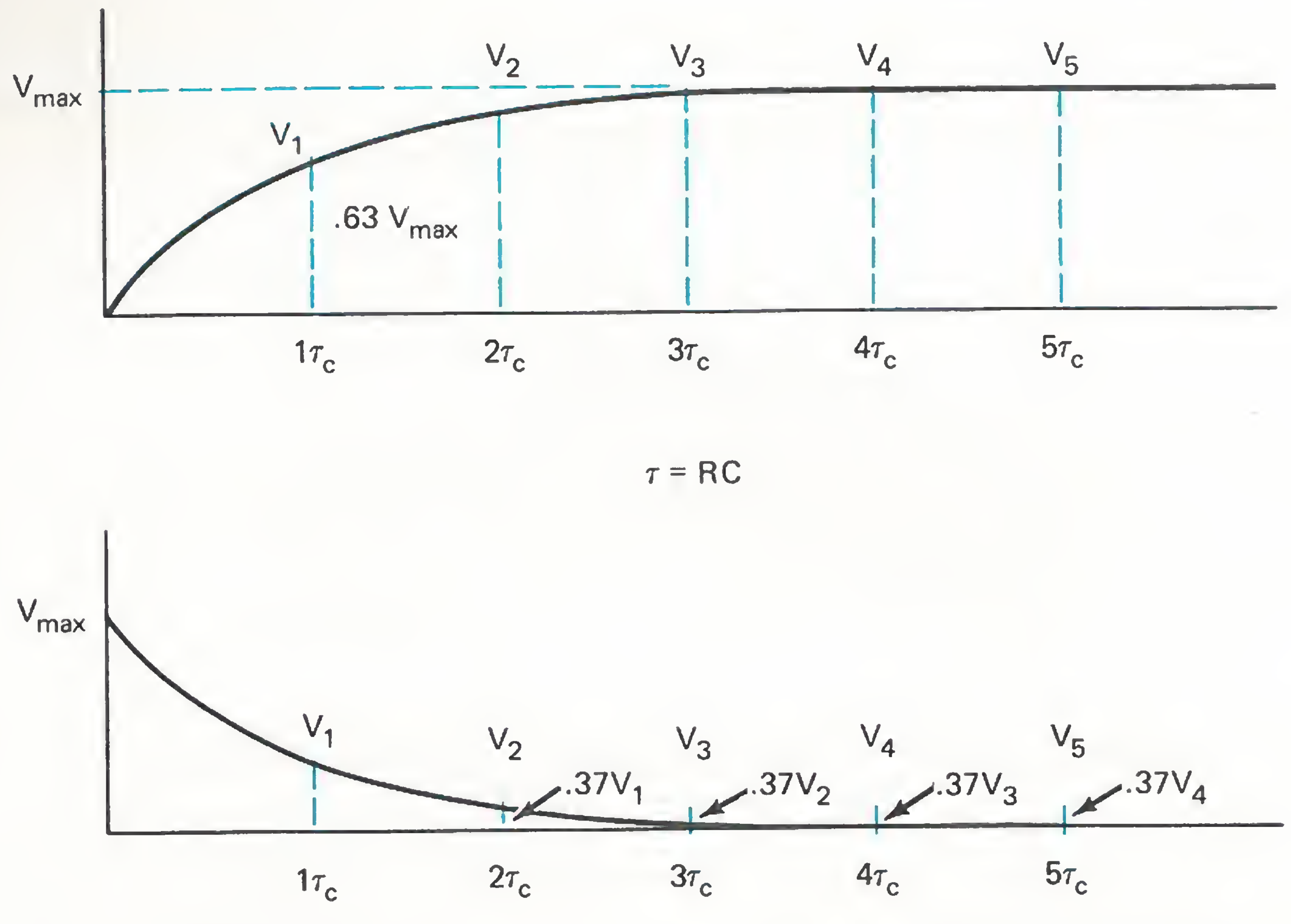


Fig. 10-12 Rise & Fall Response Of an Exponential Curve

It turns out that the capacitor will charge to 63% of its steady state value and discharge to 37% of its steady state value after one time constant. In an RC circuit the time constant is equal to the product of the resistor in ohms and the capacitor in Farads. It could be shown that after a time equal to five time constants, the value of the charging voltage can be assumed to be to its maximum charge or the discharging voltage can be assumed to be to its minimum charge. Figure 10-12 shows this graphically.

The electrical time constant of the relay depends on the resistance and inductance of the relay windings. Figure 10-13 shows a circuit that represents these windings.

Because of the characteristics of the inductor, it acts as an open circuit when first energized and does not allow current to flow in the circuit. Therefore, all of the voltage from the battery initially appears across the inductor. As time increases, the inductor will allow more and more current to flow until a time when it acts as a short circuit and allows all the current to flow. As in the RC circuit, this rate-of-change is at an exponential rate. The time constant of the LR circuit is

$$\boxed{\tau = L/R}$$

where τ = time constant
L = value of inductance in Henrys
R = resistance in ohms

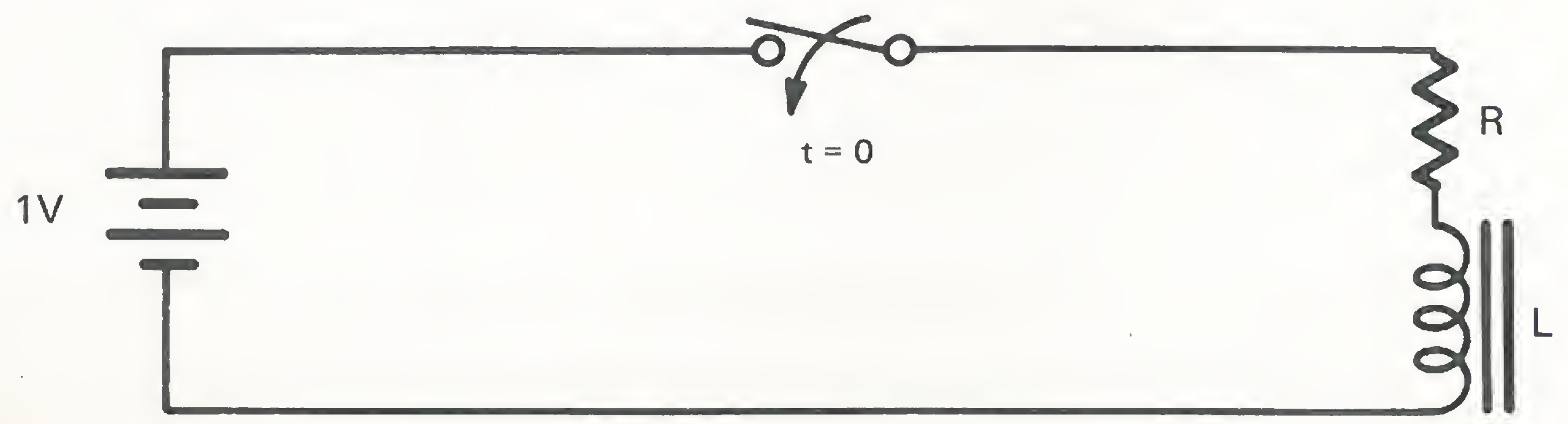


Fig. 10-13 Inductance — Resistance Circuit Of a Relay Winding

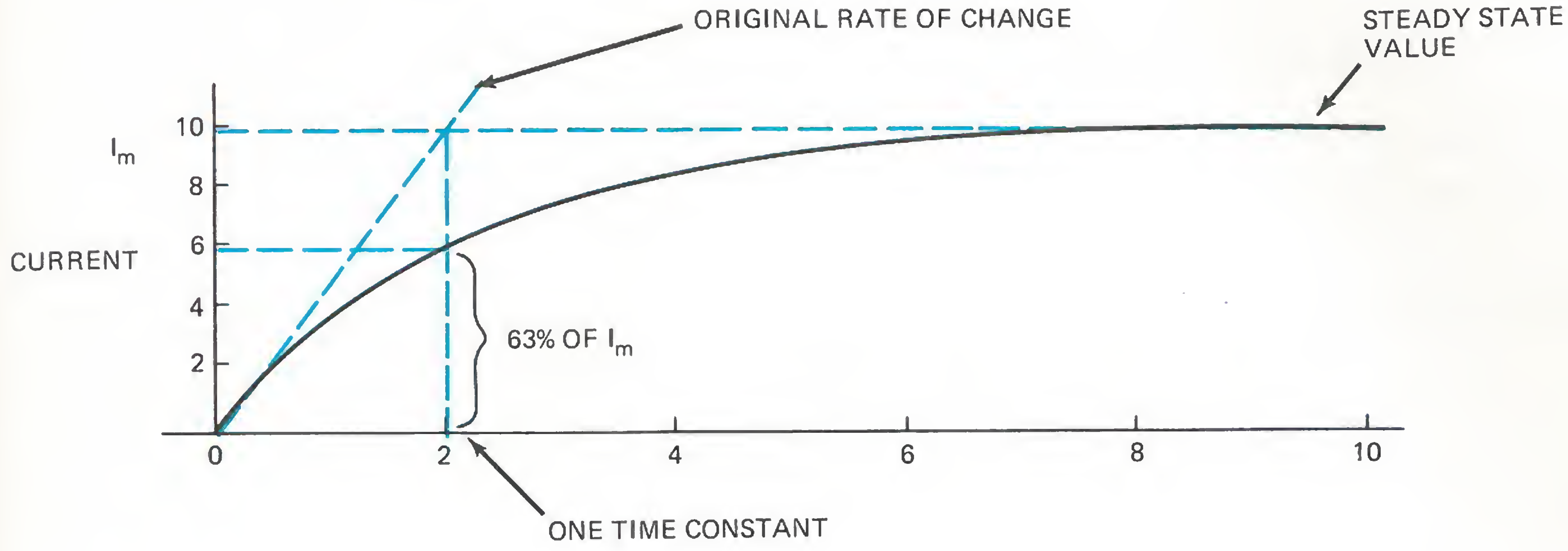


Fig. 10-14 Rise In Current In a RL Circuit

The time constant of the LR circuit is the time it would take the current to rise to its steady-state value *if* it were to continue to rise at its initial rate-of-change for the whole time interval. This is shown in figure 10-14. As in the RC circuit, the current will rise to 63% of its steady-state value after one time constant. Also, after 5 time constants, the current can be assumed to be at its maximum or minimum value, whichever is appropriate.

The exponential curves that result when working with time constants depend upon the system equations that are developed through differential equations. Figure 10-15 gives these equations for the RC and RL circuits. Similarities between these equations do exist. Also, there are similarities in the equations describing the rise and fall times of mechanical, hydraulic, and thermal systems as well, but these equations will not be given here.

It could be shown that these two equations describing the rise and fall times can be combined into one equation. This equation will *always* work for either a charging or discharging exponential and it alleviates the problem of memorizing two equations and trying to determine which equation applies when. This equation is given as

$$\boxed{Y = Y_m (Y_m - Y_o)\, \epsilon^{-x}}$$

where Y = voltage or current

Y_m = final value of voltage or current

Y_o = initial value of voltage or current

$x = \frac{tR}{L}$ or $\frac{t}{RC}$ depending on the circuit.

	Charge Equation	Discharge Equation
Capacitor	$V_c = V_o\,(1\text{-}\epsilon^{-t/RC})$	$V_c = V_o\,(\epsilon^{-t/RC})$
Inductor	$i_L = i_o\,(1 - \epsilon^{-\frac{tR}{L}})$	$i_L = i_o\,(\epsilon^{-\frac{tR}{L}})$

Fig. 10-15 Charging and Discharging Equations

MATERIALS

1 DC power supply, 0-40 volts

1 Single-pole, double-throw relay

1 Oscilloscope

1 15Ω resistor

1 VOM

PROCEDURE

1. Connect the relay as shown in figure 10-16.

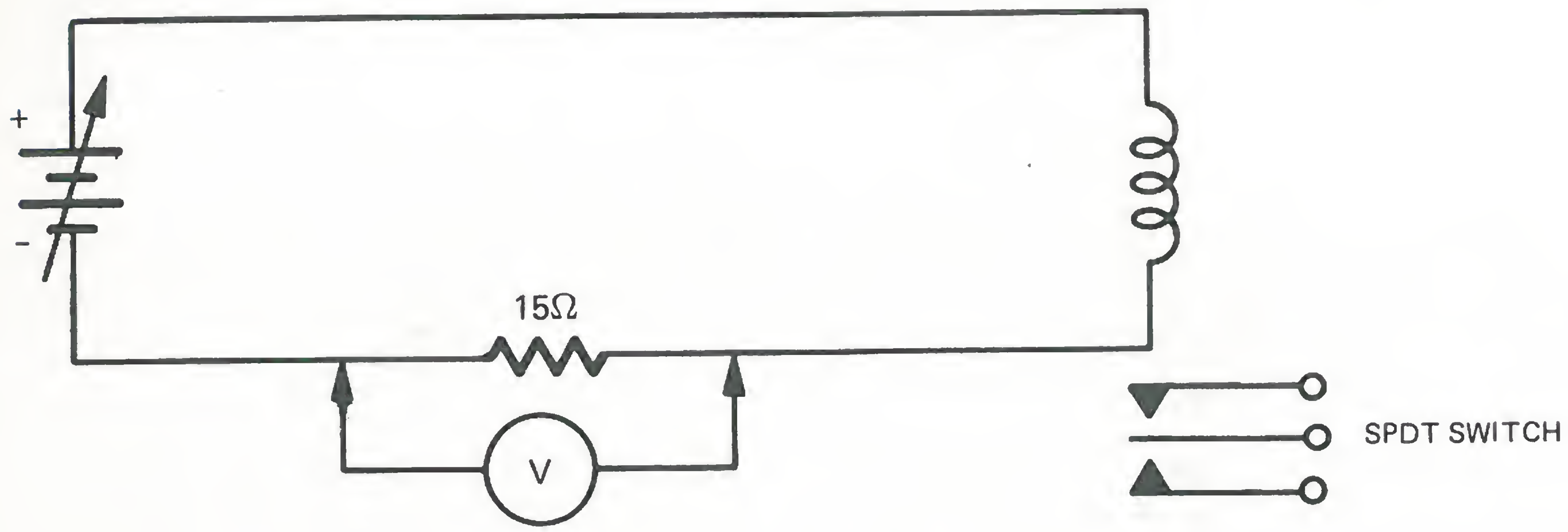


Fig. 10-16 Relay Test Circuit

2. Increase the voltage until the relay moves from one contact to the other one. Record the supply voltage and the voltage that is dropped across the resistor after the relay closes.

   Supply____________V V_R____________V

3. Connect the circuit as shown in figure 10-17.
   Scope settings: Vertical – *.1 V/CM;* Trigger and External Trigger Mode – *DC;* Horizontal Display – *Normal;* Variable Time – *5 millisec/cm.*

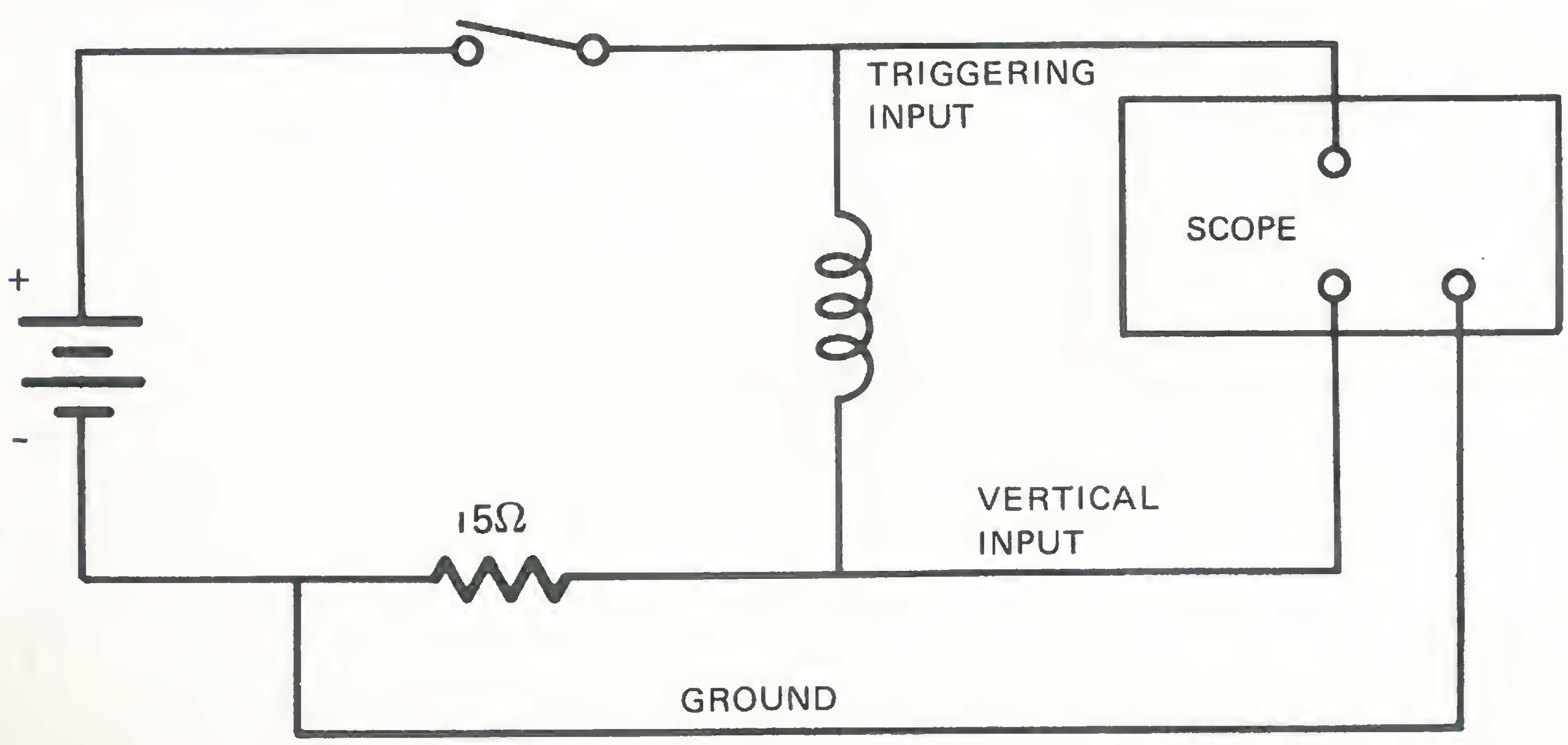


Fig. 10-17 Circuit To Test the Rise Time Of a Relay Coil

4. Set the supply voltage at the value recorded in step 2.
5. The scope settings given are only suggested and can be changed to meet the needs of the particular equipment.
6. With the switch open, trigger the scope so that a steady line appears on the face of the scope.
7. Position this line so that there are 5 cm above it.
8. Back off the stability knob until the line just disappears.
9. Throw the switch which energizes the relay. Note the resulting waveform.
10. Open the switch.
11. Repeat steps 9 and 10 until you are accustomed to the resulting waveform and can measure the time it takes to rise to the voltage dropped across the resistor that was recorded in step 2. This value is the results of the coil time constant. ____________ millisec
12. Record sufficient data to plot this waveform on graph paper.
13. Increase the supply voltage to 30 volts or to 5 volts greater than that used in step 2.
14. Repeat steps 6 – 13. ____________millisec
15. Change the circuit to look like the one shown in figure 10-18.
    Scope settings: Vertical – *10V/CM;* Trigger and External Trigger Mode – *DC;* Horizontal Display – *Normal;* Variable Time – *5 millisec/cm.*

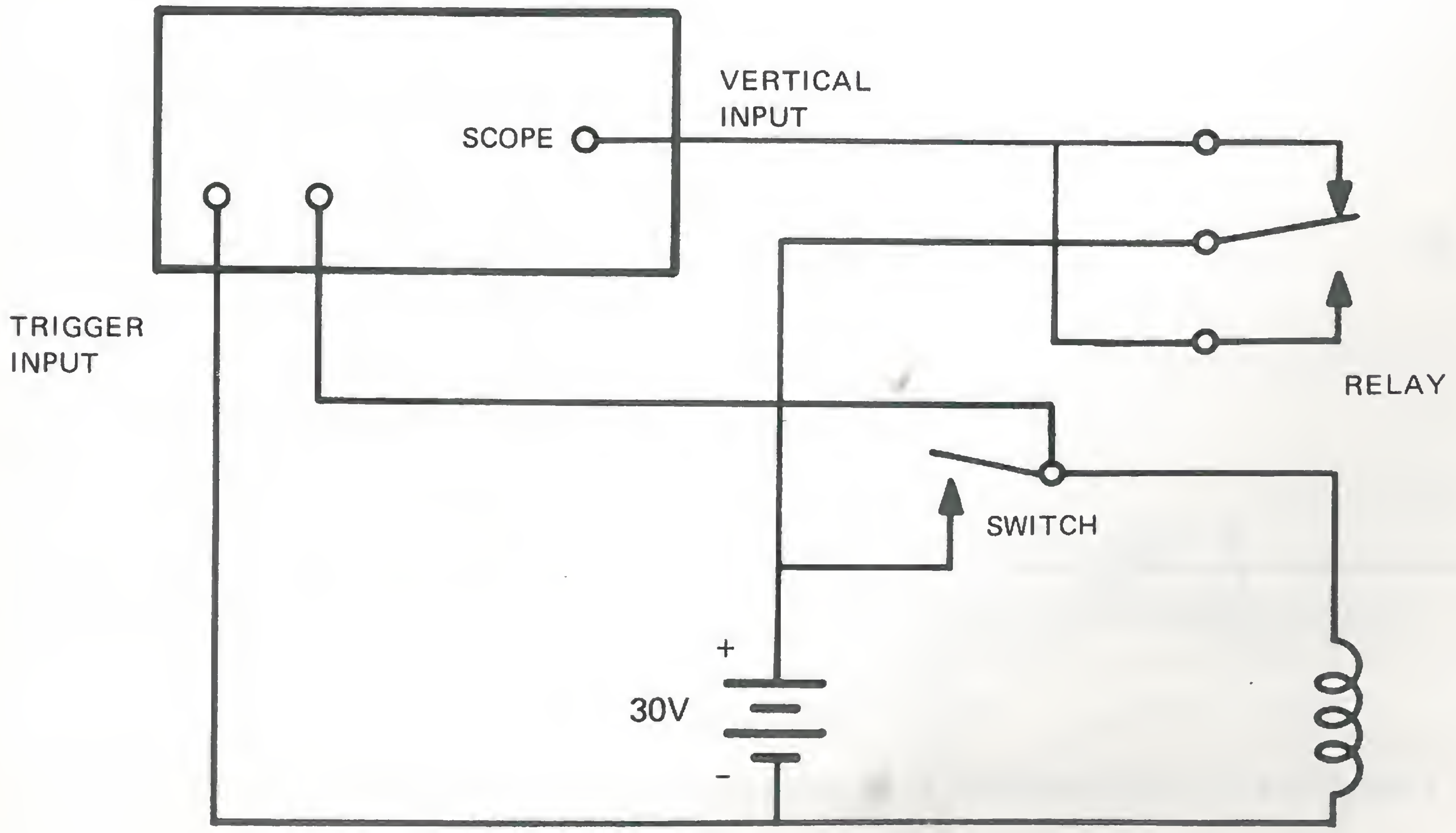


Fig. 10-18 Test Circuit For Relay Contacts

16. With the switch open, trigger the scope so that a steady line is indicated on the scope.
17. Back off the stability knob until the line just disappears.
18. Throw the switch which energizes the relay. Note the waveform on the face of the scope.
19. Open the switch again.
20. Repeat steps 18 and 19 until you are accustomed to the resulting waveform and can measure the time delay of the relay contacts.
21. Record the time that the voltage is momentarily zero. This time represents the time it takes for the contacts to move from one position to the next. __________millisec

ANALYSIS GUIDE. It should be apparent that the relay requires a certain length of time to energize and change contact positions. Explain why this reaction occurs and how it might affect the circuit in which it is connected. Plot graphs using the data in the first part of the experiment to represent the rise time of the relay coil. To the time it takes to energize the coil recorded in step 14, add the time delay of the contact closure. This total time is due to the time constant of the relay.

PROBLEMS

1. Plot the waveforms for the RC circuit shown in figure 10-19 in time sequence.

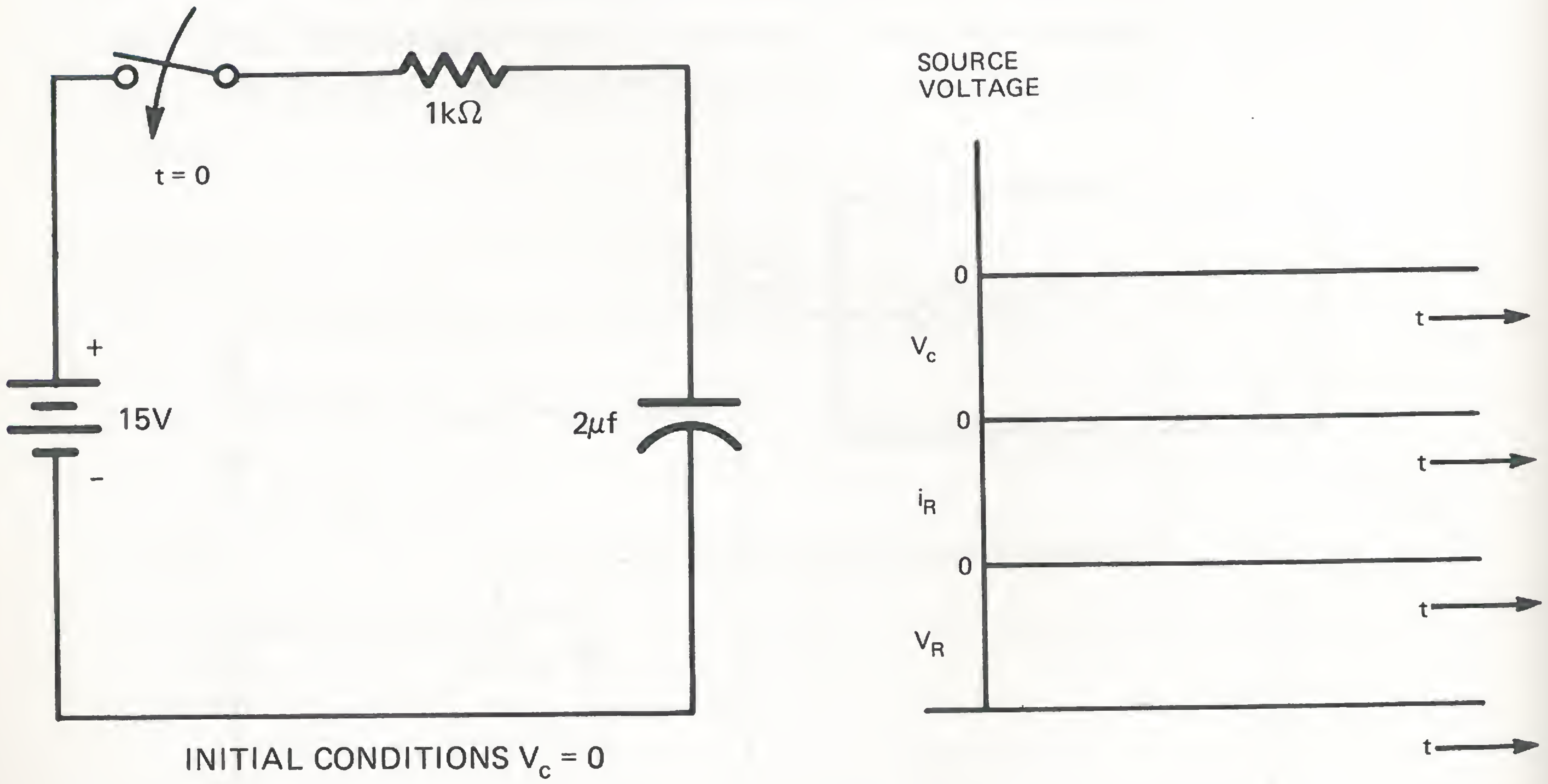


Fig. 10-19 Basic RC Circuit

2. Determine the time constant of the circuit in problem number 1.
3. Write the equations describing the rise or delay or V_C, V_R and i_R for the waveforms in figure 10-19.

experiment 11 MOTOR TIME CONSTANTS

INTRODUCTION. The electric motor is a very useful machine that is used to transform electrical energy into mechanical rotation. However, this process is not entirely instantaneous. In this experiment we will examine the time delay that results when a motor is de-energized.

DISCUSSION. For purposes of review, the basic DC motor will be investigated. The principle of the electrical-to-mechanical energy conversion in the DC motor depends on the fact that a current-carrying conductor in a magnetic field is subjected to a force which is *normal* to both the direction of current flow and the direction of the magnetic field. The armature conductors carry a band of current along the rotor in an *axial* direction, while the poles of the motor produce magnetic flux lines *across* the armature. As a result, a *tangential force* acts on the rotor. The commutator maintains the current direction in the conductors under the individual poles, so that the direction of the tangential force does not change as the rotor rotates. Figure 11-1 shows the basic parts of the DC motor.

The coils of current-carrying wire and the commutator assembly rotate within the fixed pole pieces. The fixed assembly is called the *stator* while the rotating assembly is called the *rotor.* The coils of current-carrying wire are usually imbedded in slots cut into the periphery of a cylindrical iron structure, which is laminated or built up from thin sheets of steel in order to reduce eddy current loss.

When the DC motor is first energized, the rotor speed does not instantaneously revolve at full speed. There is a *time lag* involved which is due to the motor's *time constant.* The time delay of the motor is the result of both a *mechanical time constant and an electrical time constant.*

The electrical time constant is the result of the resistance and the inductance of the armature windings. Because of these two components present in the windings, the current builds up at an exponential rate in the armature.

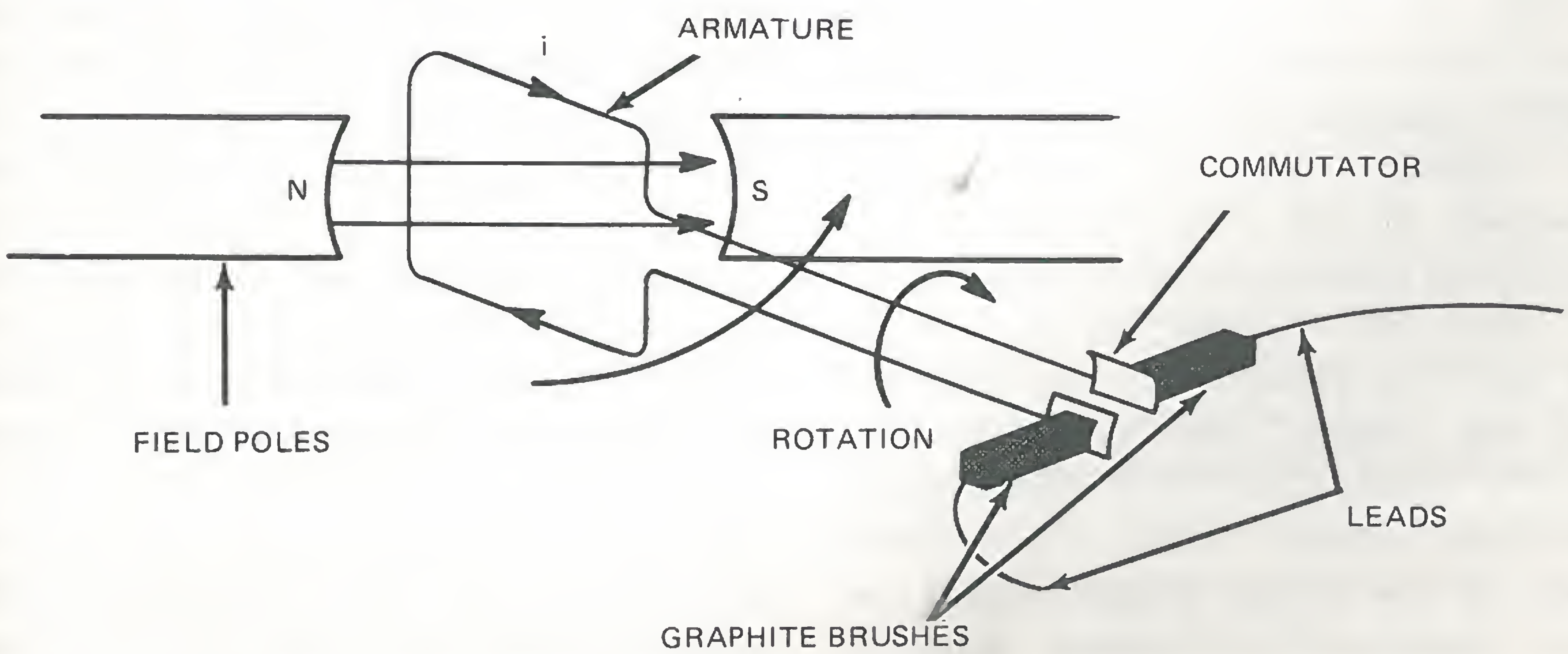


Fig. 11-1 Basic Parts Of the DC Motor

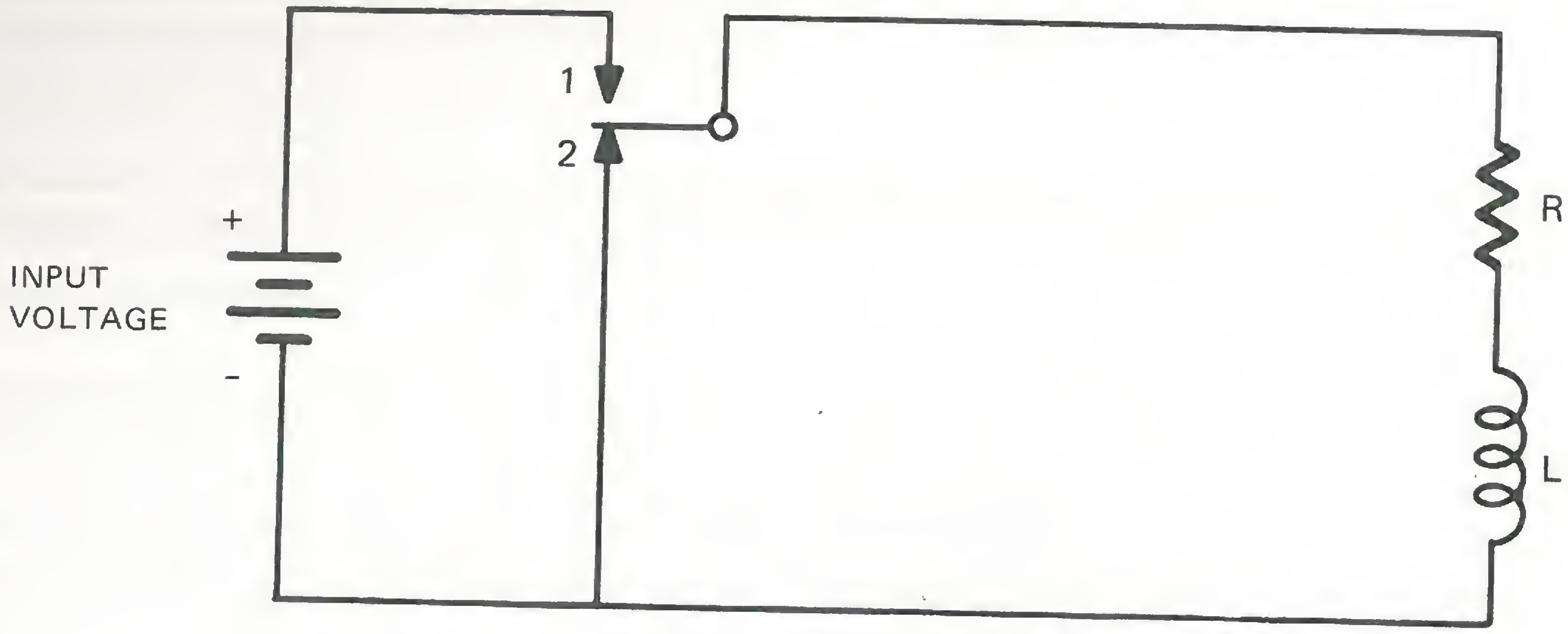


Fig. 11-2 Equivalent Circuit Of a Motor's Armature

The *torque* of a motor is defined as

$$\boxed{T = k\phi_p\, i_a} \qquad (11.1)$$

where T = torque in lb-ft
k = a constant
ϕ_p = flux per pole in webers
i_a = armature current in amps

If i_a changes exponentially, then the resulting torque T will increase at the same exponential rate. To illustrate how the torque builds up, the equivalent circuit of the motor's armature will be analyzed. Figure 11-2 shows the equivalent circuit of a typical motor.

When the relay is in position 1, the current in the circuit will not flow due to the inductor's opposition to the change in current flow. However, this will happen only momentarily as the inductor's current will exponentially build up, creating magnetic flux lines around the inductor. As the current builds up in the circuit, the voltage dropped across the resistor also builds up. By *Kirchoff's Voltage Law,* the voltage dropped across the inductor must exponentially decrease as the voltage dropped across the resistor exponentially increases. After a period of time, the current reaches its maximum value which produces a voltage drop across the resistor which is equal to the applied voltage. Consequently, the current is no longer changing but has settled to the *steady state* value of

$$I_m = \frac{E_m}{R}$$

Figure 11-3 shows the waveforms of the current and voltage responses for the circuit in figure 11-2.

After the current in the circuit has reached a steady state value, the relay is moved to position 2. When the source is switched out of the inductor's circuit, the magnetic flux lines present around the conductors will collapse back into the conductor, creating a counter emf. As they collapse, they induce a current in the wire the same as a voltage source would. Because of the inductor's characteristic of opposing any change in current flow, the current in the circuit will exponentially discharge to zero. The inductor acts as a source during this period and its voltage steps in the negative direction and discharges with a negative polarity. The current through the resistor is the same as the current in the inductor so the waveforms are the same. The voltage across a resistor is always in phase with the current; therefore, the voltage waveform is exactly like the waveform of the resistor's current.

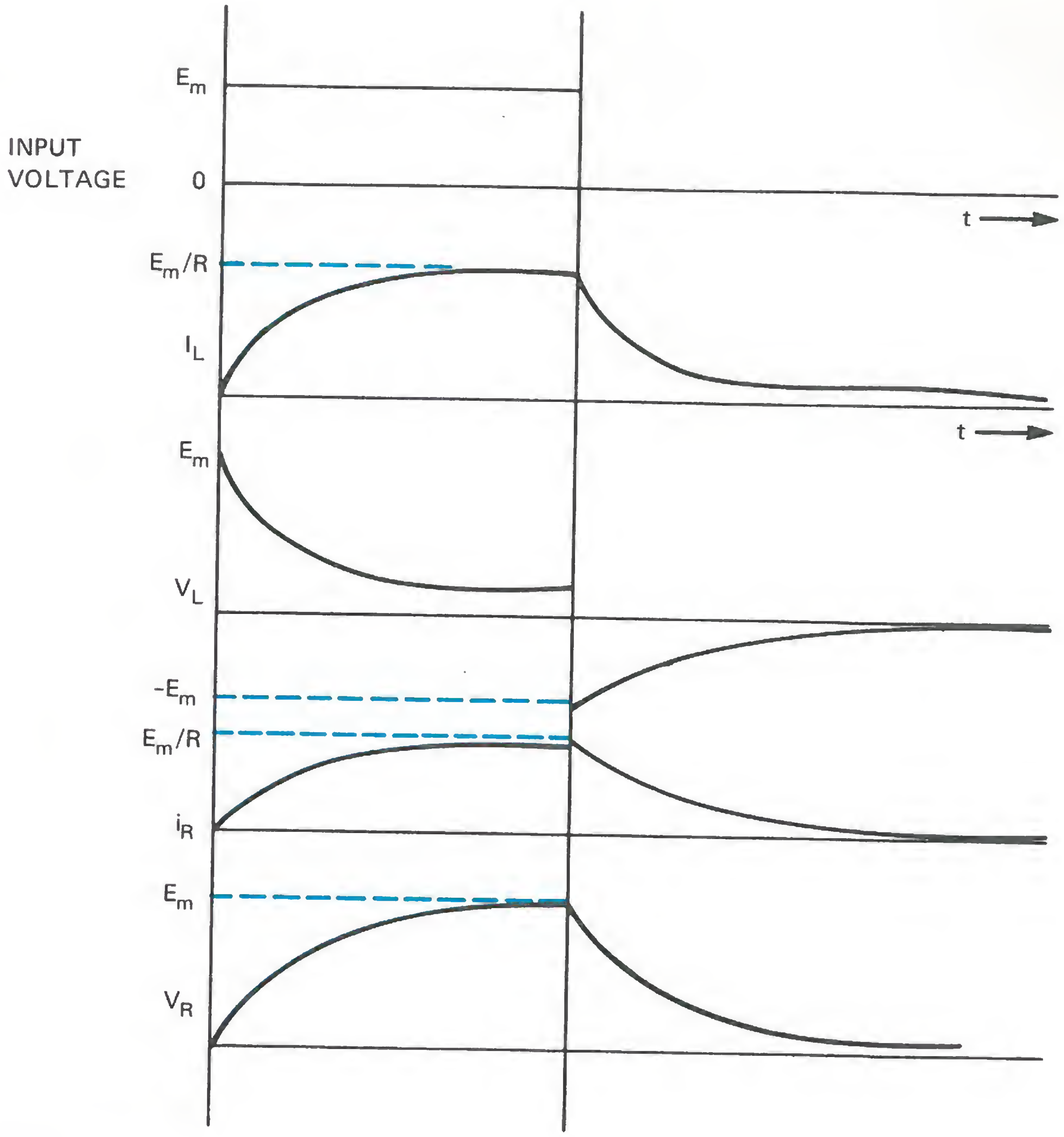


Fig. 11-3 Waveforms For Circuit 11-2

The exponential rise and delay of the current and voltage waveforms represent the electrical time delay of the motor's speed build up. The time constant, τ, involved is defined for the LR circuit as

$$\tau = L/R \text{ sec}$$

where τ = time constant in seconds
L = value of inductance in Henrys
R = value of resistance in ohms

The time is takes for the rise and fall of the current and voltage depends directly on the value of the inductor and inversely on the value of the resistor.

One time constant is defined as the time it would take the current to rise to its steady-state value if it were to continue to rise at its initial rate-of-change for the whole time interval. It turns out that the instantaneous current actually rises to 63% of its steady-state value or falls to 37% of its steady-state value after one time constant. It is also assumed that after a time interval equal to five time constants, the current will reach its steady-state value, or reach its minimum value depending on whether it is rising or falling.

An expression for the torque in equation 11.1 can be determined by substituting in the value of the armature current from figure 11-3 as it changes with time.

Referring to the equation of exponential curves, we would have for the armature's current,

$$i_a = i_L = i_R = i_o\,(1 - \epsilon^{-t/\tau}) \qquad \textbf{(11.2)}$$

where

i_a = armature current

$\left.\begin{array}{l} i_L = \text{current in inductor} \\ i_R = \text{current in resistor} \end{array}\right\}$ from equivalent circuit in figure 11-2

i_o = original armature current

t = time

τ = time constant = $\dfrac{L}{R}$

Substituting equation 11.2 into equation 11.1 would give

$$T = k\phi_p i_o\,(1 - \epsilon^{-tR/L}) \qquad \textbf{(11.3)}$$

where T = torque on the motor

k = constant

ϕ_p = flux per pole which is essentially a constant for each machine.

From the electrical standpoint, the torque in the electric motor will build up at an exponential rate which will depend on the time constant of the armature windings. The curve representing equation 11.3 would look like figure 11-4. The discharge path will delay at an exponential rate equal to

$$T = k\phi_p i_o\,(\epsilon^{-tR/L})$$

which is the equation for a delaying exponential curve.

Besides the electrical time constant in the electric motor, there is also a mechanical time constant due to the mass of the armature and conductors and the resistance due to friction in the rotor's bearings.

A mass which is rotating, such as the rotor of a motor, contains an element which is commonly known as the moment of inertia. The moment of inertia, I, of a point mass rotating at radius, r, from an axis of rotation is defined as

$$I = mr^2$$

where I = moment of inertia in lb-in-sec^2

m = mass of object in $\dfrac{\text{lb-sec}^2}{\text{in.}}$

r = radius in inches

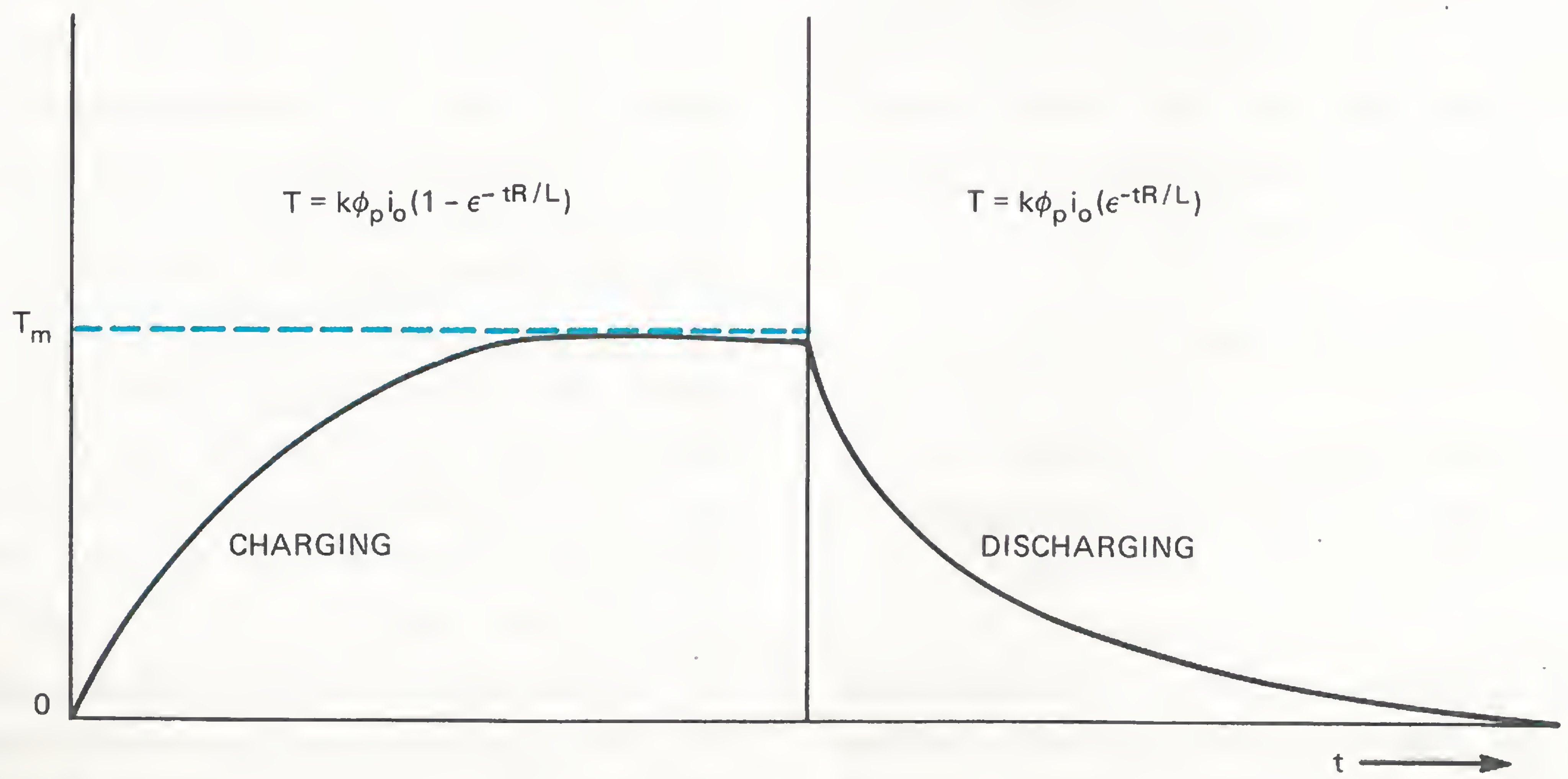


Fig. 11-4 Torque Response Of Electric Motor

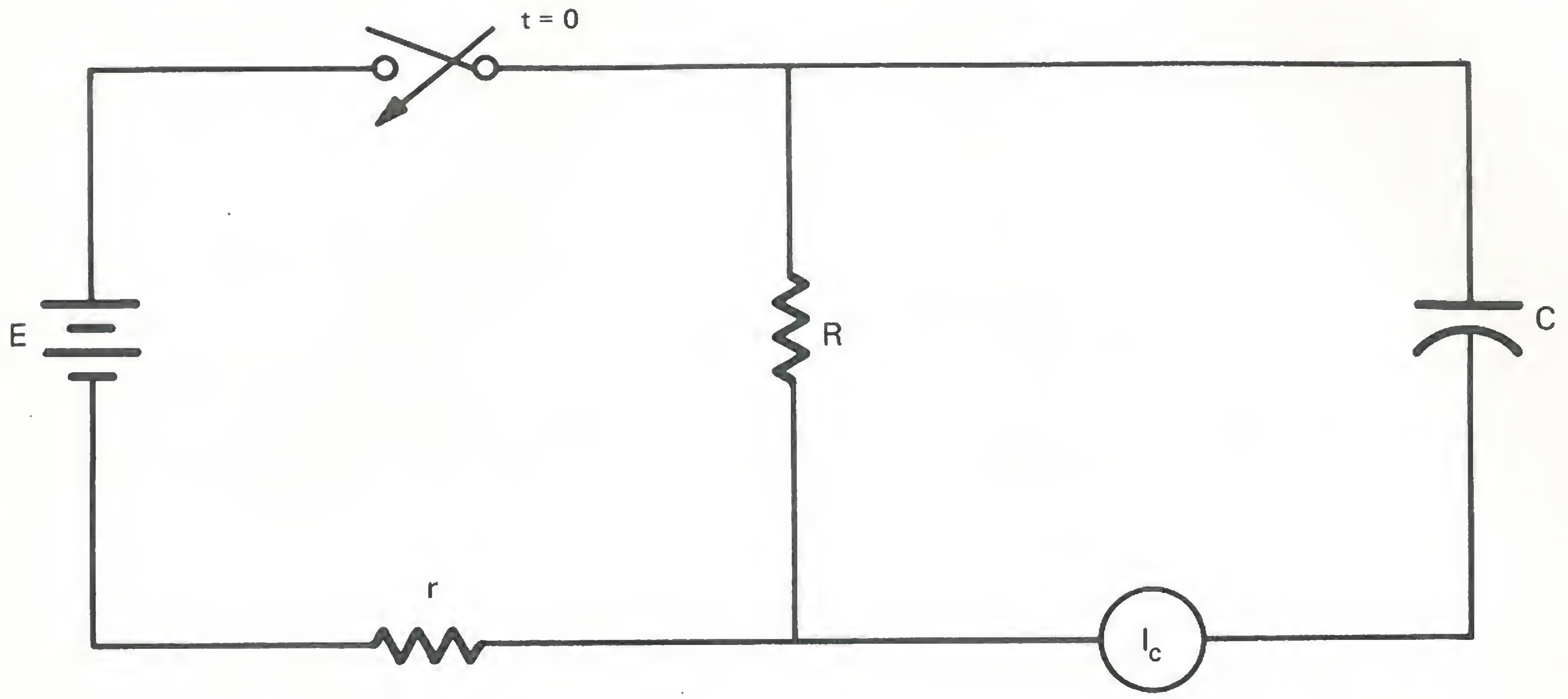


Fig. 11-5 Equivalent Circuit To the Inertia and Friction Encountered In a Motor's Rotor

The torque associated with a rotating mass depends upon the moment of inertia and the angular acceleration of the mass. This is given mathematically by

$$\boxed{T = I\,a}$$

where T = torque lb-in
I = moment of inertia
a = angular acceleration in in/sec^2

When steady-state conditions are reached, the velocity of the rotor is not changing. At steady-state, the angular acceleration is zero and the corresponding torque is zero. The rotor would run continuously at steady-state speed even after the supply voltage is removed if it were not for the opposition encountered in the rotor's bearings. This opposition is commonly known as *friction.*

The *kinetic energy* that is stored by the rotating mass is equal to

$$\boxed{KE = 1/2\ I\omega^2} \qquad \textbf{(11.4)}$$

where I = moment of inertia
ω = angular velocity in radians per second

It is this kinetic energy that causes the rotor to keep rotating for a time after the electric energy is disconnected. It is this kinetic energy which eventually goes to zero because of the friction involved in the bearings. To understand how this energy decreases to zero, an analogous circuit will be used.

The parallel RC circuit is chosen because the voltage across the resistor R and the voltage across the capacitor C are equal when the switch is first closed. This is analogous to the rotor's velocity in the motor. The velocity of the rotor mass and that of the bearings are both equal when the motor starts. The small resistor r is used only to give the circuit an RC time constant when first energized. The capacitor and the resistor R are analogous to the inertia and the friction of the rotor respectively. When the switch is first closed, the capacitor acts as a short circuit momentarily and current does not flow through the resistor R. However, as the capacitor exponentially charges to its final steady-state value, current exponentially increases through the resistor causing the

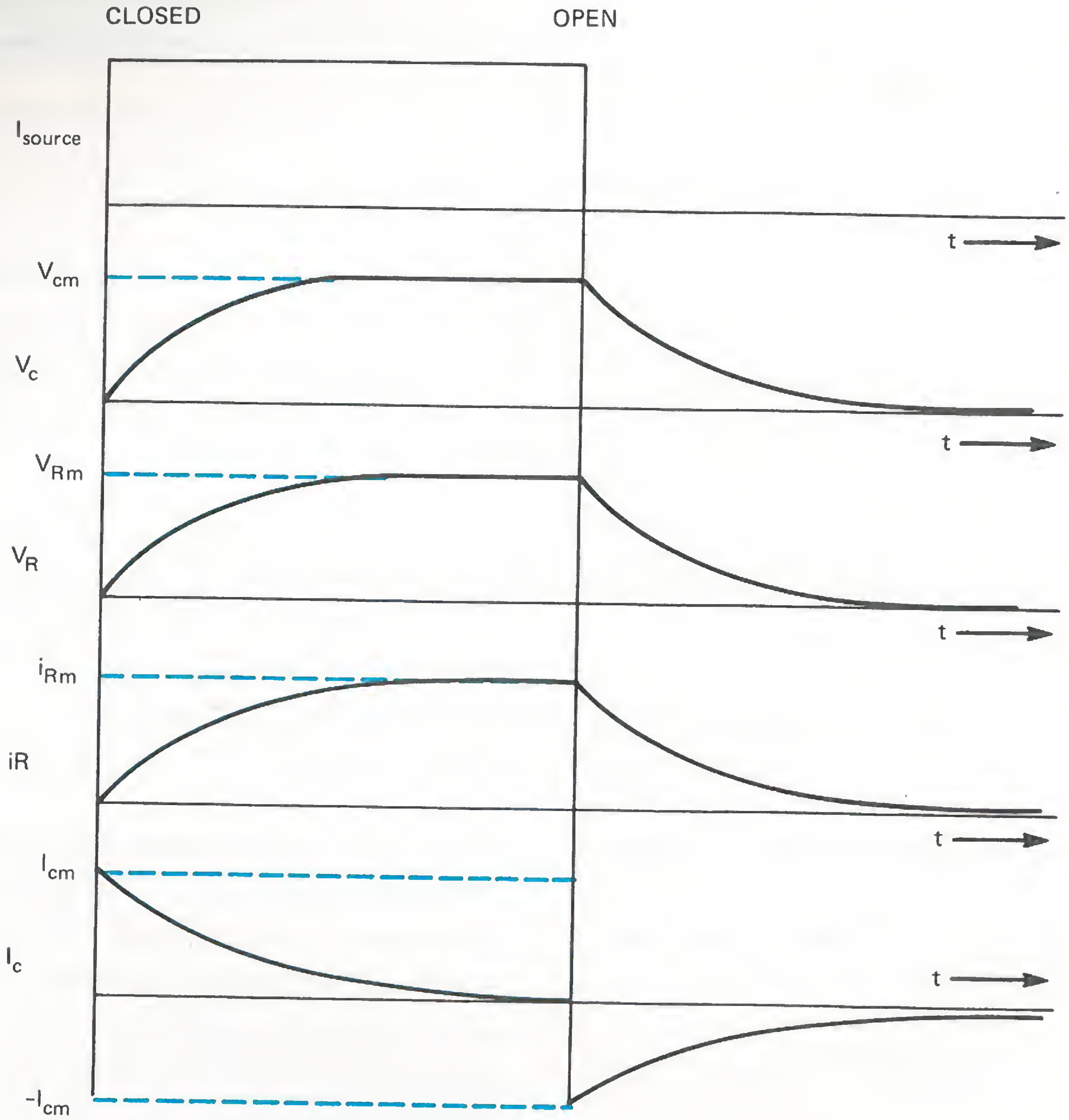


Fig. 11-6 Waveforms Of the Circuit In Figure 11-5

voltage across the resistor to increase. The current I_C exponentially decreases to zero. The corresponding waveforms are shown in figure 11-6.

When the switch is opened, the source is switched out of the circuit and the capacitor discharges its current through the resistor R. The capacitor voltage exponentially decreases to zero and the resistor's voltage exponentially decreases to zero. The current through the capacitor reverses direction and decreases to zero with a negative polarity. Notice that the sum of i_R and I_C is equal to the source current at any time t. This has to be the case in a parallel circuit.

Originally the circuit in figure 11-4 was used as an equivalent circuit to represent the inertia and resistance present within the motor. Now the waveforms of the equivalent circuit must be interpreted in terms of inertia and friction.

Figure 11-7 shows the analogy between the mechanical-rotational components and the electrical components found in the electric motor.

With these analogies in mind, one can apply the waveforms of figure 11-6 to the mechanical motor. When the switch is closed at t = 0, there is a torque produced on the

MECHANICAL-ROTATIONAL	ELECTRICAL
Torque	Current
Velocity	Voltage
Inertia	Capacitor
Bearing Friction	Resistor

Fig. 11-7 Analogous Components

rotor that must overcome the inertia and friction present. The torque produced is momentarily at a maximum. However, the torque reacting on the bearings is exponentially building up while the torque required to overcome the inertia is decreasing to zero. After five time constants, the inertia's torque is zero and the rotor could run indefinitely if it were not for the torque present acting on the bearings. As would be expected, the velocity of the inertia and the velocity of the rotor's bearings are equal and exponentially increase to a maximum value. When the input power to the motor is cut off, the torque acting on the motor's conductor is equal to zero. The velocity of the inertia and the rotor's bearings decrease exponentially to zero. The torque acting on the rotor's bearings also decreases to zero. The torque acting on the inertia reverses direction and decreases to zero in a direction opposite to the torque on the rotor's bearings. To understand this, refer to figure 11-8.

During the time the motor is energized, the torque that turns the rotor is the difference in the input torque created by the magnetic flux lines being cut by the armature conductors and the torque produced in the rotor's bearings. The reaction torque shown in figure 11-8a represents the friction torque. After the motor becomes de-energized, there is no longer a torque on the rotor from the flux lines being cut. The torque which is acting on the rotor is only the reaction torque which is in the opposite direction and eventually stops the rotor from turning. The corresponding curves are given in figure 11-9.

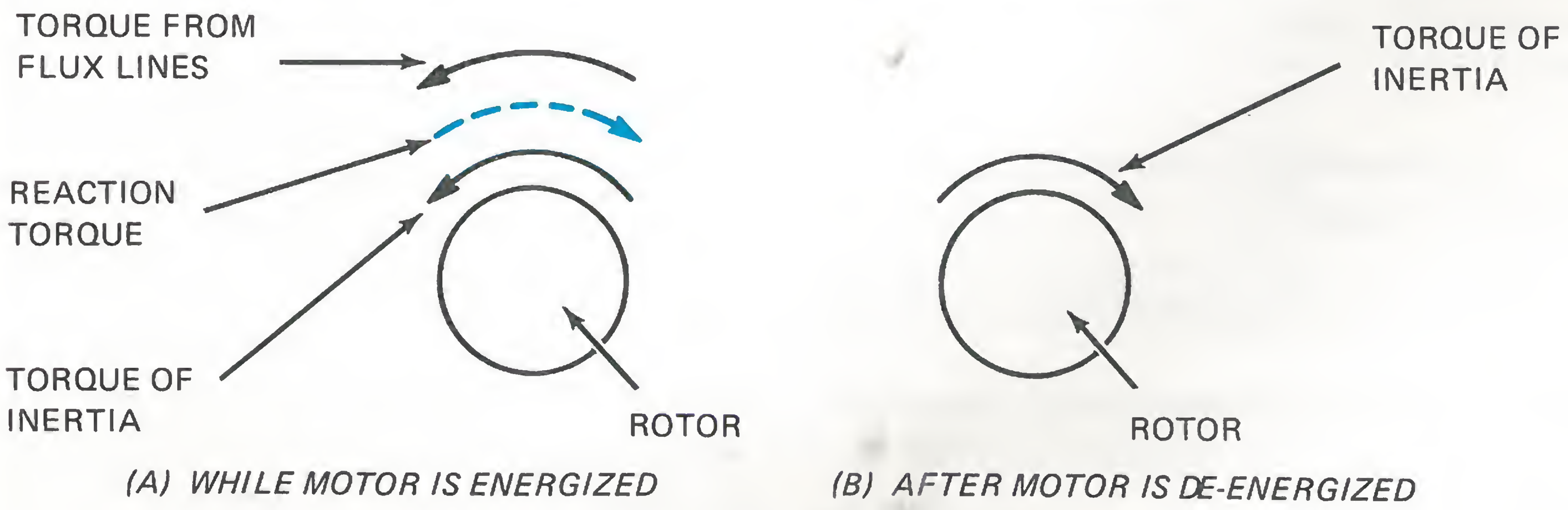


Fig. 11-8 End View Of Rotor

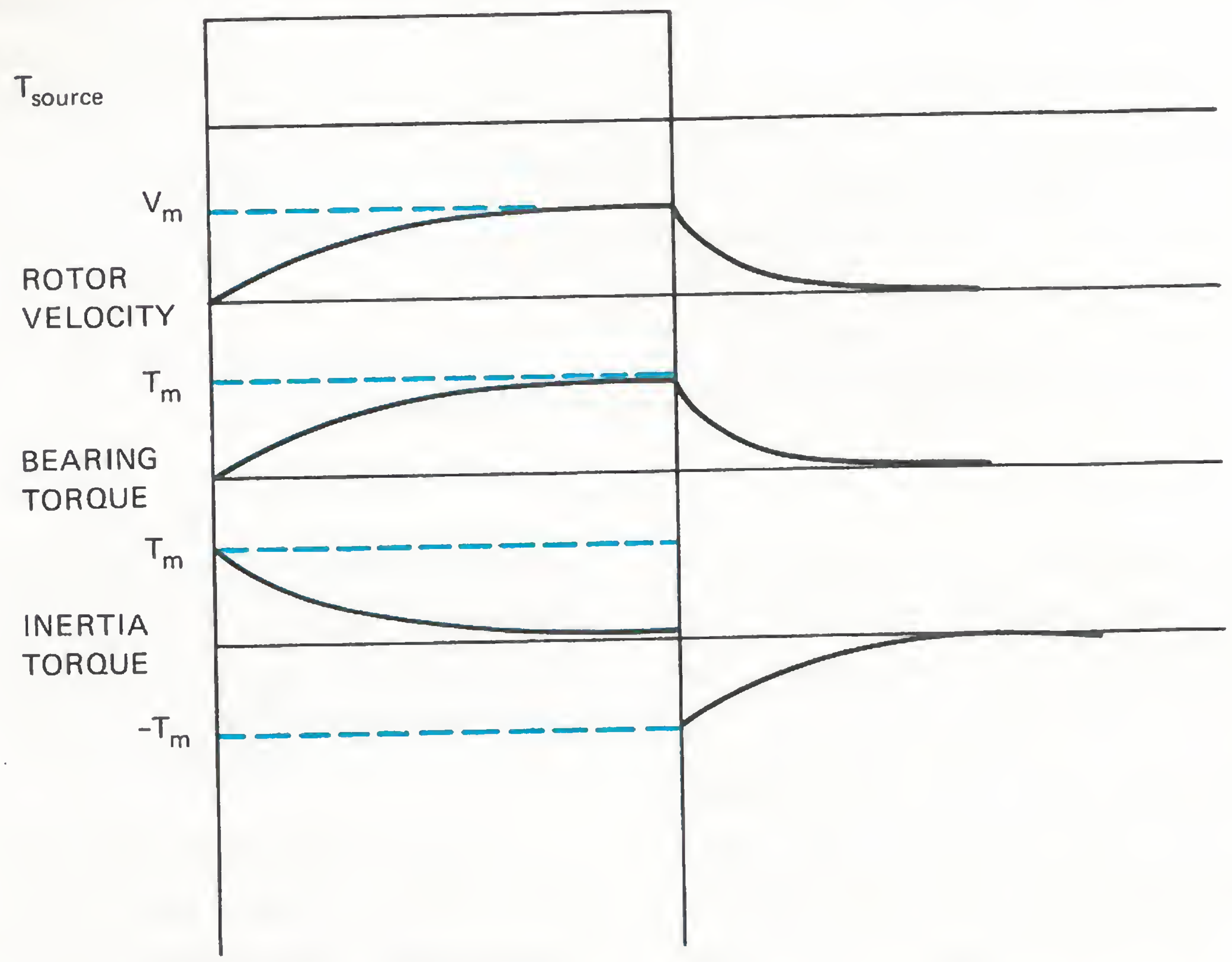


Fig. 11-9 Curves Of a Motor When Energized and De-Energized

The time constant for the mechanical components of the motor follow all of the same rules as the time constant for the electrical components in the motor. The velocity of the rotor will reach 63% of its steady-state speed or decrease to 37% of its steady-state speed after one time constant. After a time interval of five time constants, the velocity of the rotor will be either at steady-state speed or be at its minimum speed.

The equation for the rotor's velocity as it builds up speed is

$$\boxed{\omega = \omega_O (1 - \epsilon^{-t/\tau})} \qquad \textbf{(11.5)}$$

where ω = angular speed in radians per second
ω_O = steady-state speed
t = time
τ = time constant

The equation for the rotor's velocity as it decreases to zero is given by

$$\omega = \omega_O \, \epsilon^{-t/\tau} \qquad \textbf{(11.6)}$$

The time constant for the mechanical inertia and friction components in the motor is given by

$$\boxed{\tau = \frac{I}{B}} \qquad \textbf{(11.7)}$$

where τ = time constant in seconds
I = moment of inertia in lb-in-sec^2
B = damping coefficient of rotating frictional component in lb-in-sec/rad

Substituting the time constant of equation 11.7 into equations 11.5 and 11.6 will give an expression for the increasing and decreasing velocity of the motor's rotor as shown in figure 11-10.

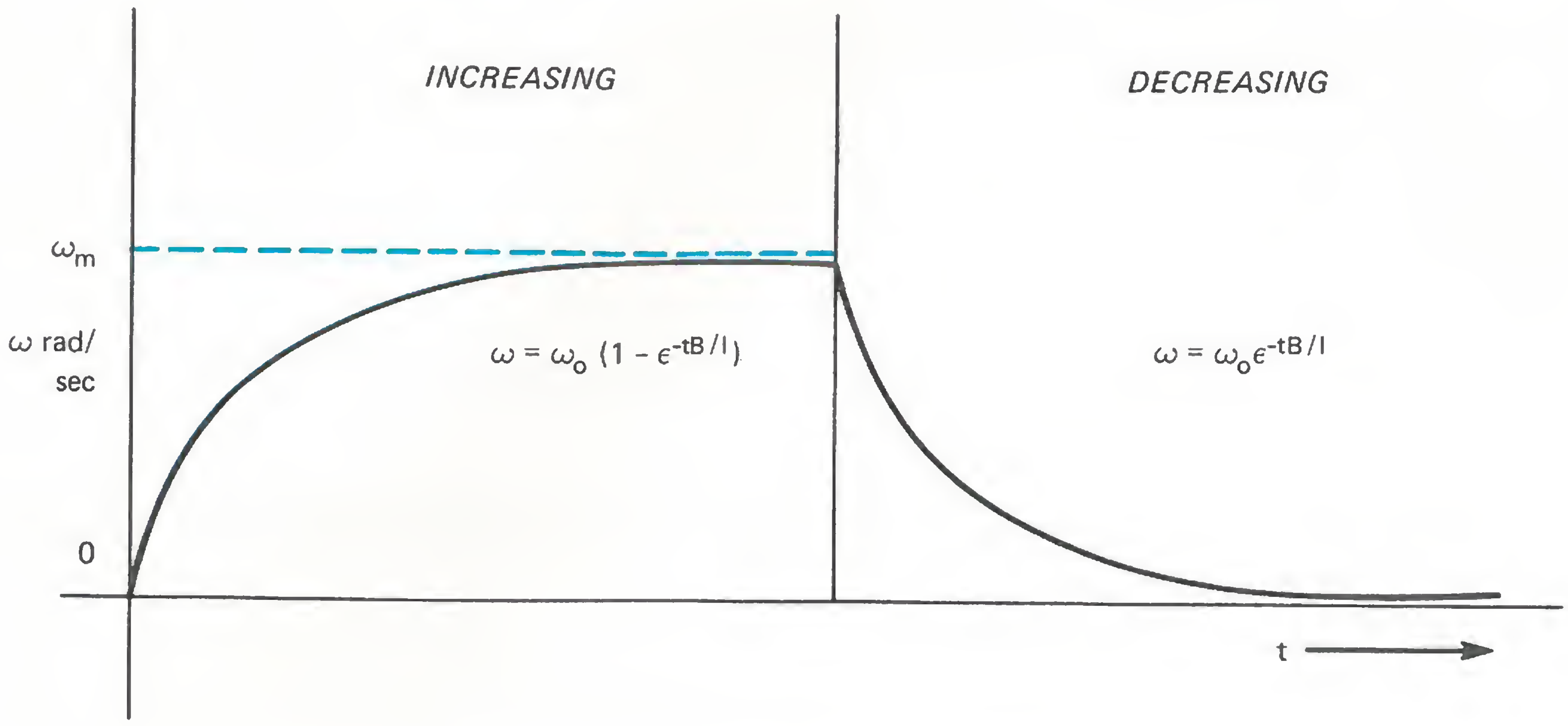


Fig. 11-10 Increasing and Decreasing Rate Of Rotor's Velocity

If the equation for the decreasing velocity of the rotor is substituted into equation 11.4, an expression for the kinetic energy of the turning rotor could be expressed

$$K.E. = 1/2\, I\, (\omega_o \epsilon^{-tB/I})^2$$

From this equation it should be obvious how the mechanical time constant of the motor influences the rotating components of the motor. As time increases, the value of $\epsilon^{-tB/I}$ becomes smaller. The resulting product becomes very small and eventually all of the kinetic energy goes to zero.

To determine the decreasing response of the motor as it slows down from a steady-state velocity we will use the circuit shown in figure 11-11.

When the relay is in position 1, the test motor will build up speed to a steady-state value. After the motor is running at a steady speed the relay will be moved to position 2.

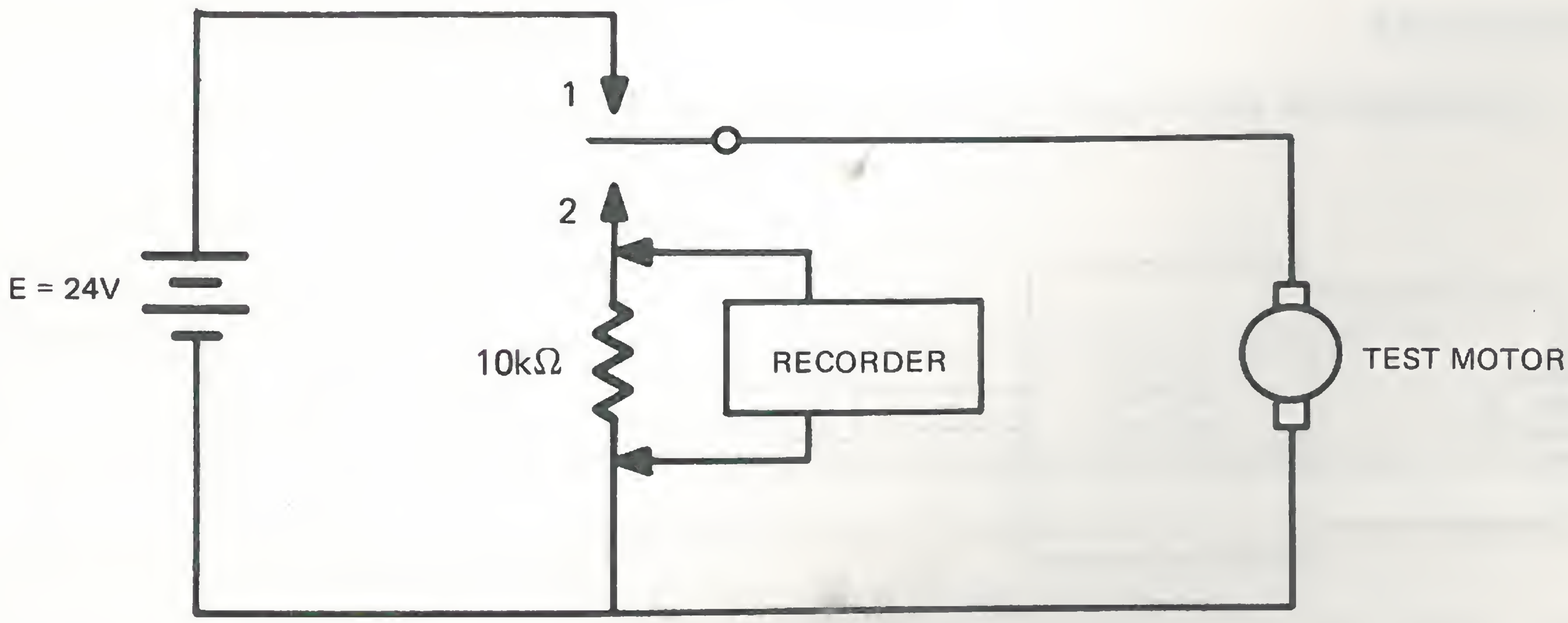


Fig. 11-11 Experimental Circuit

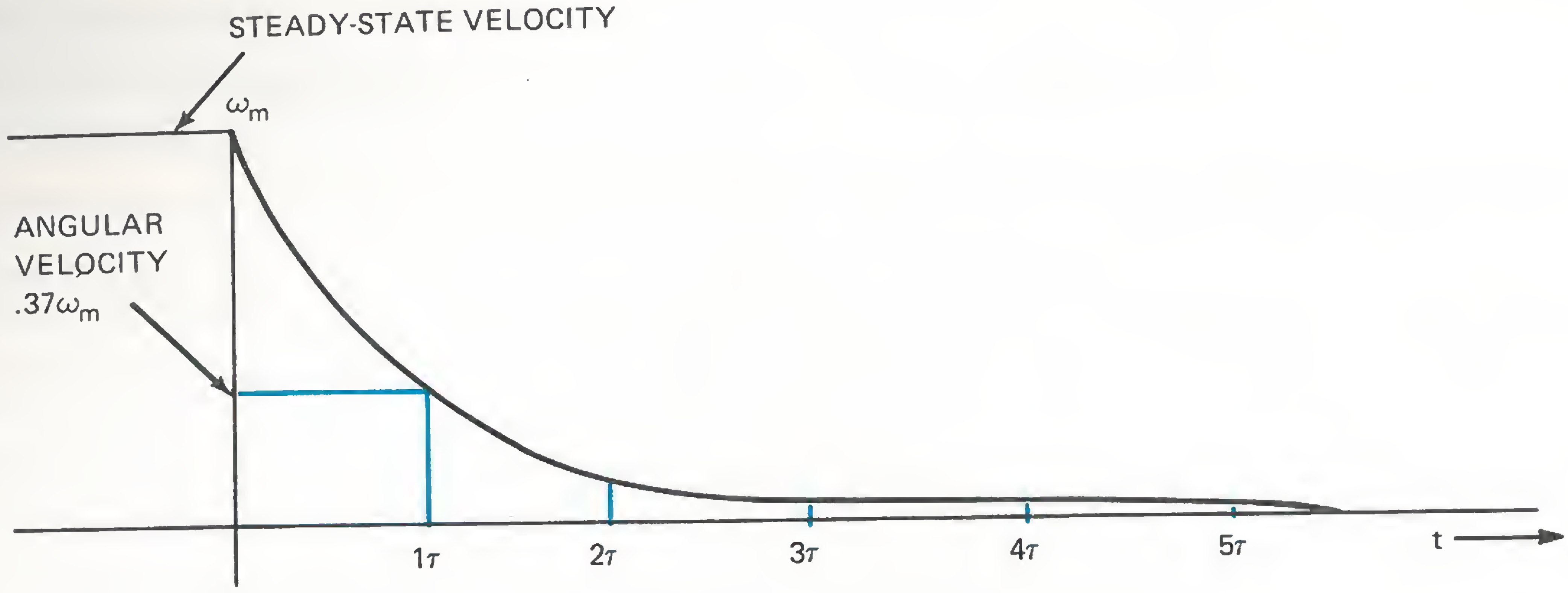


Fig. 11-12 Time Constant Of a Decreasing Exponential

As the motor runs down, the emf produced by the motor-converted generator will produce a current through the resistor. The corresponding voltage drop will be recorded on a *strip chart recorder.* The exponential curve produced will be the result of the inertia of the motor producing a voltage as the armature turns in the magnetic field. From this response curve the time constant of the motor can be determined by measuring the time it takes to decrease to 37% of the steady-state velocity.

MATERIALS

1 VOM

2 28V DC motors

1 Motor shaft coupling

1 DC power supply

1 10k resistor

1 Stroboscope

1 Single-pole, double-throw switch

1 Sheet graph paper, 10 X 10 divisions in cm

1 Strip chart recorder

3 Flywheels – different sizes

PROCEDURE

1. Connect the two motors as shown in figure 11-13.

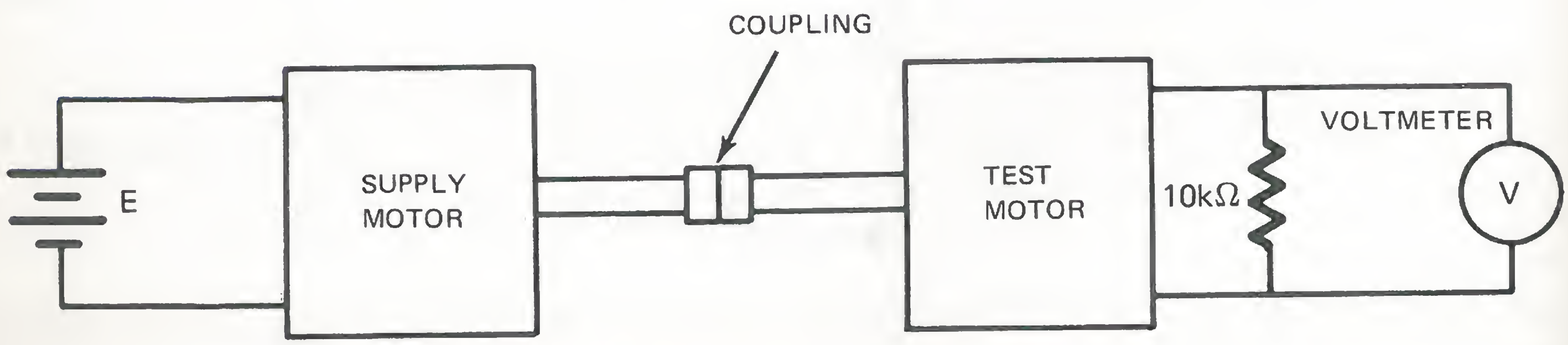


Fig. 11-13 Motor Connection To Determine Output Voltage Per RPM

2. With the test motor running at 8000 RPM, record the voltage dropped across the resistor in the table in figure 11-16.

3. Record the output voltage for each RPM given in the data table.

4. Rearrange the circuit as shown in figure 11-14.

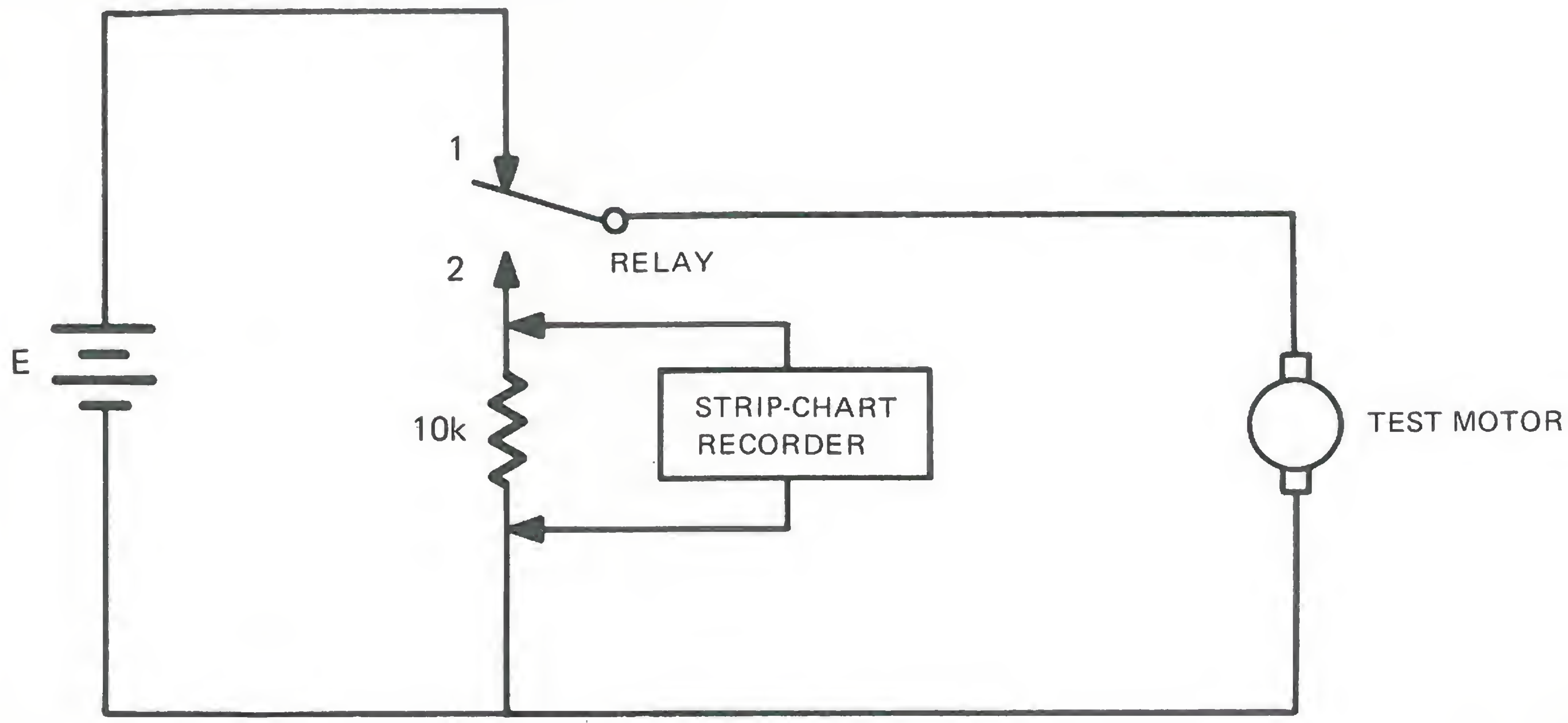


Fig. 11-14 Experimental Circuit To Determine the Time Constant Of a Motor

5. The strip chart recorder should be set up as follows: paper feed = 100 mm/sec or equivalent, the stylus travel should be maximum.

6. With the relay in position 1, run the motor speed up to 4000 RPM.

7. After the motor speed is running at 4000 RPM, turn on the paper feed of the recorder.

8. When the paper is running, switch the circuit to position 2.

9. When the motor speed is reduced to zero, turn off the paper feed on the recorder.

10. Rerun this part of the experiment if the recorded voltage is not a readable form. It may be necessary to increase the speed of the paper feed or increase the volts per cm input value.

11. Rerun the experiment with the flywheels attached to the shaft of the test motor. Label each curve one at a time so that they do not get mixed up.

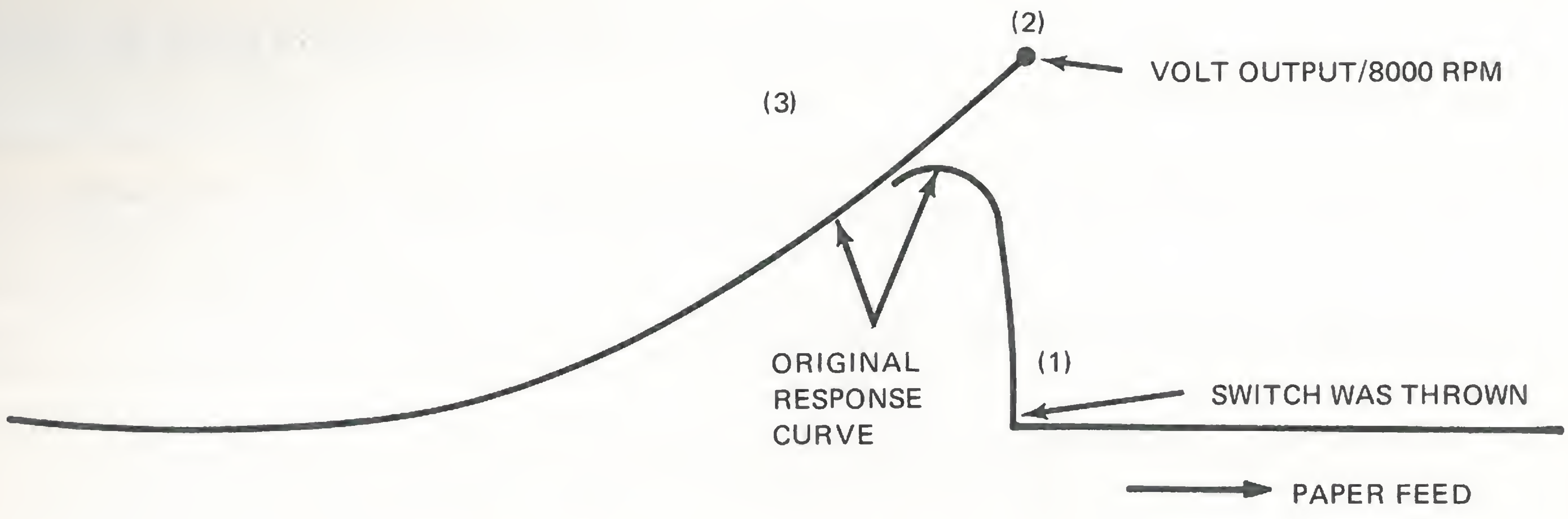


Fig. 11-15 Extrapolating Response Curve

12. Label the voltage axis for each curve by converting the known input voltage per mm to the graph paper. It may be necessary to extrapolate the response curves to zero time due to the slow response of the stylus movement. To do this follow the following procedures: (1) locate when the switch was thrown on the recorder paper, (2) raise above this point to a voltage value corresponding to the output of the motor-generator at 8000 RPM, (3) from this point, draw a smooth exponential curve down to the response curve. It should intersect approximately where the stylus caught up with the paper's speed.
13. Using the data from figure 11-16, indicate on the response curve the speed of the rotor at different time intervals.
14. Plot all the response curves on one sheet of graph paper and label the vertical axis angular speed in RPM and the horizontal axis time in seconds.
15. Determine the time constant for each curve.

ANALYSIS GUIDE. The electric motor, like most other machines, is a very useful piece of equipment. However, it has some properties that make it slow in responding to input voltage and slow in response to stopping its rotary motion. Explain how this time lag is developed in the motor, what the results are from the response curves, and how it might affect the operation of a piece of equipment that needs to start and stop instantaneously.

PROBLEMS

1. Determine the electrical time constant of a motor which has 100 Ω resistance and 200 Henrys inductance in the armature windings.
2. Plot the waveforms of E_1 V_L, V_R, and i_R versus time for the circuit shown in figure 11-17 for each value of R.

   Determine the time constant for each value of resistance. After five time constants, switch the relay to position number 2 and plot the discharge curves for each value of resistance.

RPM	Voltage
5000	
4000	
3000	
2000	
1000	
0	

Fig. 11-16 Data Table of Output Voltage Versus RPM

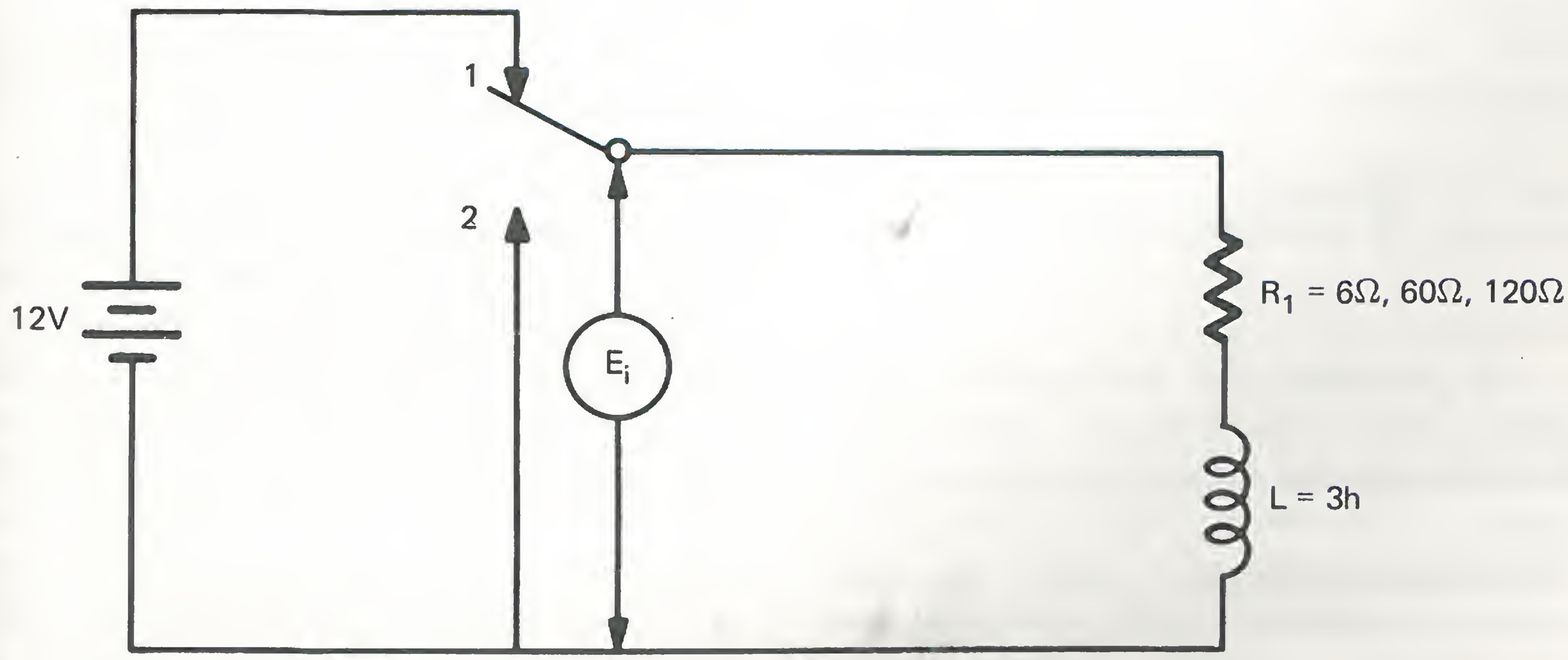


Fig. 11-17 A simple RL Circuit

experiment 12 THERMAL TIME CONSTANT OF A TRANSFORMER

INTRODUCTION. Besides electrical and mechanical *time constants* present in different electromechanical devices, there may also exist a time constant due to the temperature changes within electrical wires or bearing surfaces. In this experiment the principle of the *thermal time constant* will be illustrated with the use of a transformer.

DISCUSSION. You have probably noticed that when current flows in a wire, the wire gets hot. When a transistor or other circuit component is used in a circuit, it may also get hot. In fact almost all devices that are used to transfer, transform, dissipate and store energy heat up in the process. When these devices are de-energized, they cool back down to their original temperatures. The temperature of these devices increases and decreases at an exponential rate and not instantaneously because of the thermal time constant characteristic of the device. Each device has its own time constant characteristics and the rate of temperature rise and fall will be different for each device.

The electrical time constant of an RC circuit depends upon the capacitance and the resistance within the circuit. The electric time constant of an RL circuit depends upon the inductance and the resistance within the circuit. Therefore, electrically speaking, the time constant can be equal to either

$$\boxed{\tau = RC \text{ or } \tau = L/R}$$

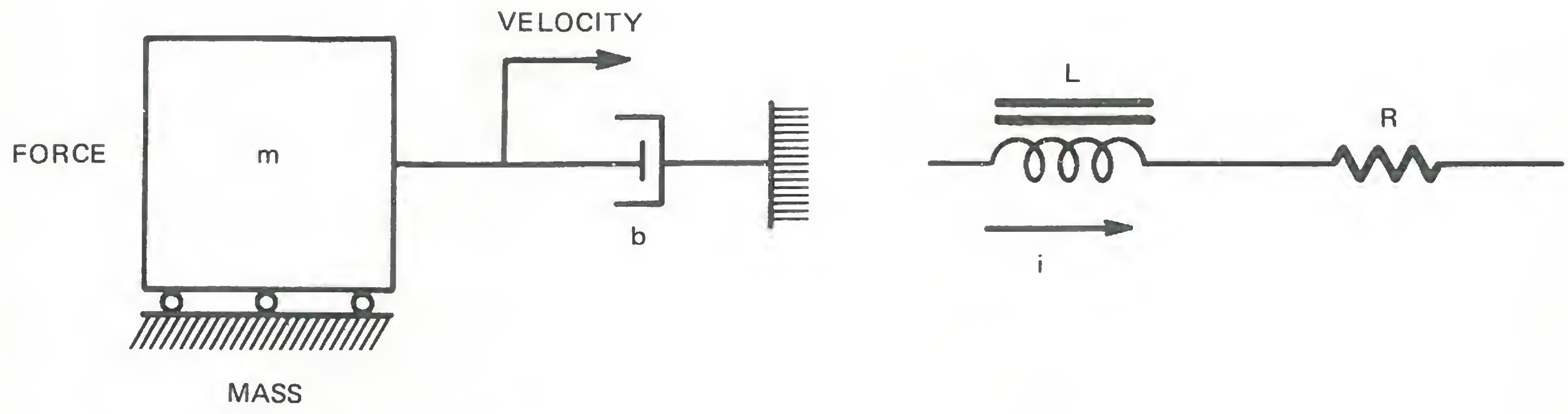
In a *mechanical translational system* there is also a time constant present which depends upon the components making up the system. The three characteristics of a mechanical translational system are *mass, friction* (sometimes called *damping*) and *deformation* (usually referred to as *compliance.*)

It could be shown that mass and inductance are analogous characteristics within their respective fields. To go along with this, a spring and a capacitance and a damper and a resistor also show analogous characteristics across their separate disciplines. With these characteristics in mind, a mechanical system can be thought of in terms of an electric circuit. To help point this out, the mechanical translational system in figure 12-1a is shown with its analogous RL circuit in figure 12-1b.

The mechanical prototype shown in figure 12-1 shows, in schematic, the shock absorber found on the automobile. The mass represents the car mass and the damper represents the piston action of the shock absorber. The electric circuit shown is chosen because of the common current through the elements of the circuit. This is equivalent to the common velocity of the mass and damper's piston shaft.

Other analogies could be shown that would utilize masses with springs, parallel RL circuits, and series and parallel RC circuits.

Besides the analogies drawn between the electrical circuits and the mechanical translational systems, other systems can be shown to approximate the same characteristics as these two systems. The equations that represent the characteristics of all the systems are equivalent, except for the variables designating the components involved. By knowing the characteristics of one system, a broader understanding of the other systems is possible.



(A) MECHANICAL *(B) ELECTRICAL*

Fig. 12-1 Analogous Mechanical and Electrical Circuits

The other systems involved are *mechanical-rotational, fluids* (hydraulics and pneumatics) and *thermal.*

In this experiment we will be involved with thermal time constants. Thermal resistance and thermal capacitance are the two elements present which affect the thermal time constant present within a device.

The capacity of a given material or combination of materials to store internal energy by virtue of a temperature rise when it receives a net flow of heat is determined by its mass and its *specific heat,* C_p.

The specific heat of a substance is the quantity of heat needed to raise the temperature of a unit mass of that substance by one degree. In the English system, the specific heat of a substance is expressed in BTU per pound-Fahrenheit degree. The numerical value of specific heat of any substance is the same in the metric system as it is in the English system.

The specific heat of water is always 1; in other words, it takes 1 BTU of heat to raise the temperature of 1 pound of water 1 Fahrenheit degree. The specific heat of water is very high compared with that of most other substances. The specific heat of copper, at ordinary temperatures, is 0.093 BTU per lb-Fahrenheit degree. One BTU of heat added to one pound of copper will raise its temperature by more than 10° F. The same quantity of heat added to 1 lb. of water raises its temperature only 1 degree.

We know that the climate of places near lakes and other large bodies of water is cooler in summer and warmer in winter than the climates in other places at the same latitude and altitude. This is explained by the fact that the specific heat of water is much higher than that of land or air. The large body of water absorbs more heat than does an equal mass of the surrounding land or air for each degree that the temperature changes. As a result, the large body of water will gain its heat much more slowly than the surrounding air. When the temperature of the air starts dropping, the water will lose its temperature much more slowly than the air. In effect, this gradual change in heat is brought about by the time constant of the water. The only other element present which affects the time constant is the resistance of surroundings to the heat flow.

When the specific heat of a substance is known, the heat gained by a given mass of the substance as its temperature increases is easily determined. If m is the mass of the body in lbs. and C_p is its specific heat, the number of BTU's it must gain to become 1 Fahrenheit degree warmer is given by the product of m and C_p. From this it follows that the heat gained by a substance when the temperature changes by a known amount can be found by

$$\boxed{\Delta H = m\, C_p\, (\Delta T)}$$

where ΔH = heat gained in BTU's
m = mass in lbs.
C_p = specific heat in BTU's per lb.–°F
ΔT = temperature change – °F

The specific heat depends somewhat on the constraints applied to the material during heating. For example, heating at constant *pressure* yields a specific heat different from that obtained by heating a constant volume.

All materials offer some resistance to heat flow, which is evidenced by the fact that the temperature drops in the direction of heat flow through a material. When the material offers a large degree of resistance to heat flow, it is usually called an *insulator* and its *thermal conductivity* is low. A material through which heat flows relatively freely is called a *conductor* and its thermal conductivity is high. There are three methods by which heat can travel: *conduction, convection* and *radiation.*

Many substances, notably metals, have the ability to transfer heat by way of *conduction.* If a conductor such as a bar of copper is heated at one end, the heat travels steadily through the bar until the whole bar is warm. The temperature does not flow instantaneously to the other end but takes a certain length of time depending on the mass of the body and its resistance to heat flow as described earlier. The transfer of heat by conduction occurs because of the transfer of *kinetic energy* from atom to atom on a microscopic scale within the material.

Substances which do not conduct heat well are such materials as wood, cork, air, and water. These materials or some combination of each is usually incorporated into insulating materials to be used in homes, automobiles, and industry where heat flow is not wanted. Conductors are used when it is desired to aid heat in traveling from one place to another or to dissipate heat from circuit components such as *transistors.*

The process by which heat is transferred through a liquid or gas by means of currents is called *convection.* To heat a substance that is a poor conductor of heat, it is necessary to bring each part of it near the heater to be heated directly. In liquids and gases which are poor conductors of heat, this is done by the formation of a current inside the liquid or gas. The current circulates the liquid or gas continually so that each part of it is brought in direct contact with the heater over and over again. When a liquid or gas is heated from below these currents are set up automatically and are called convection currents.

The hot air expands and becomes less dense than the surrounding colder air and starts to float upward. The colder air now close to the source of heat is heated and in turn is also displaced upward and the surrounding air moves down to take its place. This process continues and results in the formation of currents in which newly heated air continually rises while the colder air moves in to take its place. The convection currents continue to circulate and eventually bring every part of the air into contact with the warm air.

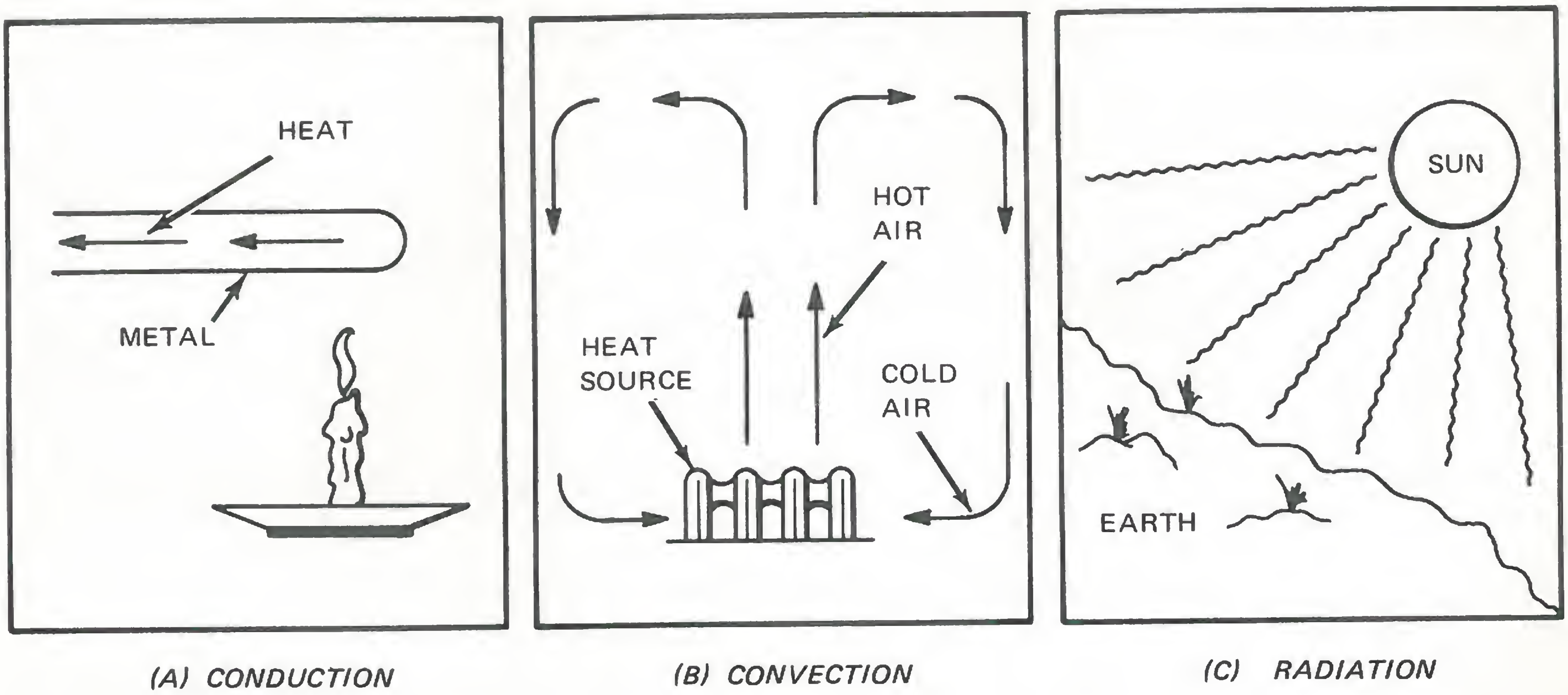


Fig. 12-2 Three Methods of Heat Transfer

Radiation is the transfer of heat by process of waves known as *infrared rays.* One only has to stand in the sun to become aware of the great quantity of heat it pours down upon the earth. Since the sun's heat travels through the near-vacuum that exists in the space between the sun and the earth, it cannot reach the earth by either conduction or convection. The method by which it does reach the earth resembles that by which light travels.

Infrared rays are invisible but they resemble light waves in many ways. They belong to the electromagnetic family of waves, all of which travel at near 186,000 miles per second, the speed of light. They are reflected by mirrors and other polished, shiny, or white surfaces and are absorbed by black, rough surfaces. They can also be focused, like light, with curved mirrors or lenses.

All objects, whether warm or cold, are constantly exchanging heat with each other by emitting and receiving heat in radiant form. The higher the temperature of a body with respect to its surroundings, the faster it will radiate heat to them; the lower the temperature of a body with respect to its surroundings, the faster it will absorb radiant heat. Radiant heat is noticed particularly when one is near a hot object such as a fire or hot radiator.

A thermal resistance, unlike mechanical, electrical, and fluid resistances, dissipates no energy since the net heat flow is always zero. It also stores no energy, since no work is done during the heat flow process.

When the thermal capacitance and the thermal resistance are combined, the resulting time constant is produced. The thermal capacitance is given by

$$C_t = mC_p$$

where C_t = the thermal capacitance in BTU/°F
C_p = specific heat in BTU/lb – °F
m = lb-mass

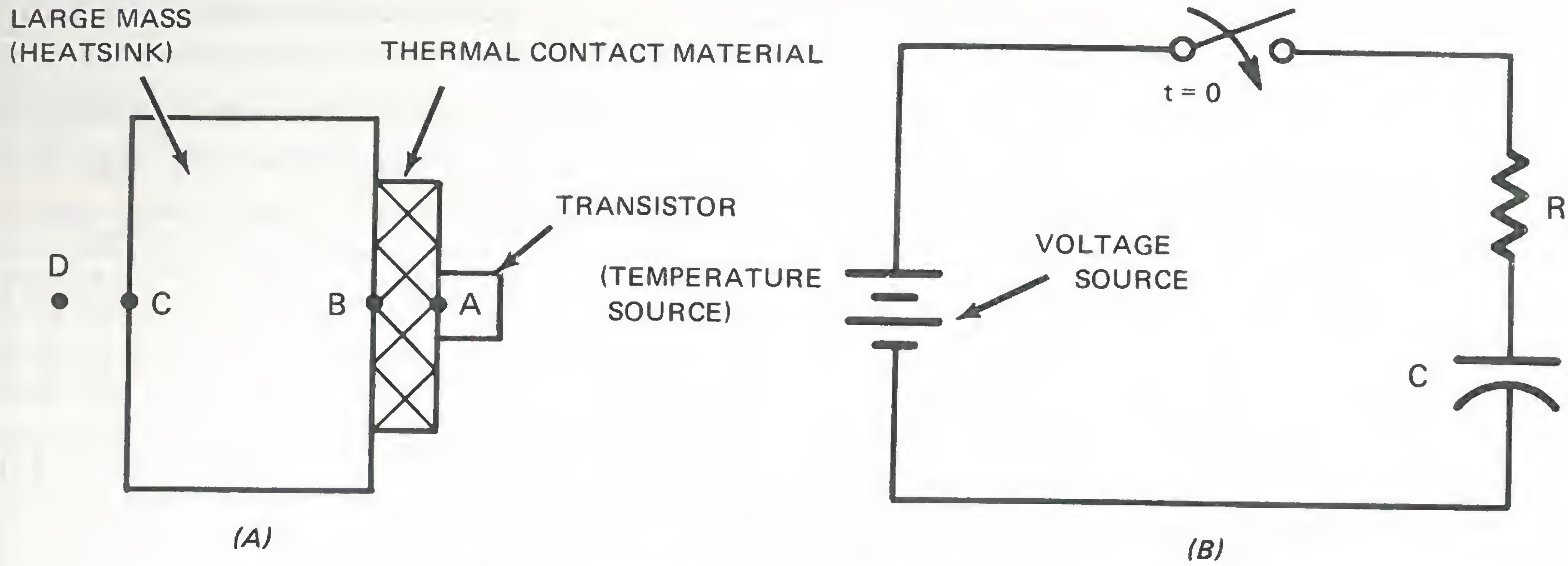


Fig. 12-3 Electrical Equivalent of a Thermal System

In most applications of electromechanical devices, the equation describing the thermal resistance is due to the conduction of heat and is given by

$$R_t = \frac{\ell}{\theta_c A}$$

where R_t = thermal resistance $\frac{°F - sec}{BTU}$

θ_c = thermal conductivity of material in BTU/sec.-in.-°F

A = cross-sectional area in square inches

ℓ = length in inches

The thermal resistance due to convection is given by

$$R_t = \frac{1}{C_h A}$$

where C_h = coefficient of heat transfer in BTU/°F-sec.-in^2

A = cross-sectional area in square inches

The product of the thermal resistance and the thermal capacitance will give the time constant for a thermal system:

$$\boxed{\tau = R_t C_t} \qquad (12.1)$$

where R_t depends on whether the thermal resistance is due to conduction or convection.

The transistor thermal arrangement shown in figure 12-3a can be represented by a series RC circuit as shown in figure 12-3b.

The heat flow from the temperature source through the resistance (insulation) occurs in much the same fashion as the electron flow in the electric circuit which is produced by a voltage source and flows through the resistor.

The exponential curves for both systems shown would be very similar. The only difference might be the rate of rise and fall of the curve which depends on the system's time constant. The curves for both systems are shown in figure 12-4.

As in the electrical, mechanical, and fluid systems, the time constant of a thermal system can be defined as the amount of time it takes the temperature to rise to 67% of its steady-state value. After a length of time equal to 5 time constants, the temperature is assumed to be at steady-state conditions.

In this experiment, after 5 thermal time constants, the temperature will be assumed to be a steady-state condition.

In this experiment the thermal time constant will be investigated by making use of

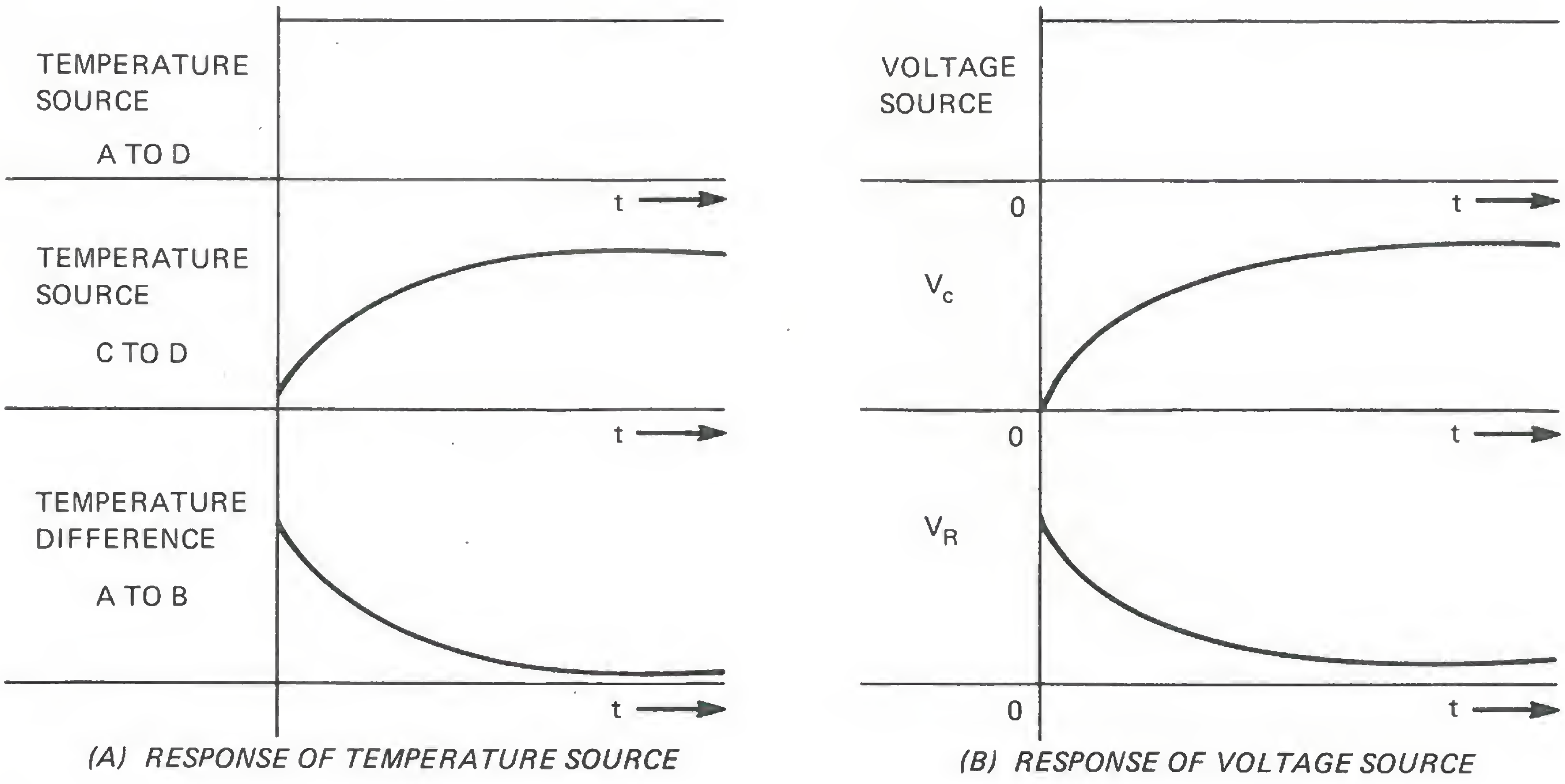


Fig. 12-4 System Curves from Figure 12-3

the fact that a transformer will heat up when being used to transform voltage from one level to another.

The transformer is a common application of *mutual inductance*. The transformer, as shown in figure 12-5, has the primary winding N_p connected to a voltage source that produces alternating current, while the secondary winding N_s is connected across the load resistance R_L.

The purpose of the transformer is to transfer power from the primary, where the generator is connected, to the secondary, where the induced secondary voltage can produce current in the load resistance connected to N_s.

Although the primary and secondary are not connected to each other, power in the primary is coupled into the secondary by the magnetic field linking the two windings. The transformer is used to provide power for the load resistor R_L, instead of connecting R_L directly across the generator, whenever the load requires an AC voltage higher or lower than the generator voltage. By having more or less turns in the secondary than in the primary, the transformer can step up or step down the generator voltage to provide the required amount of secondary voltage.

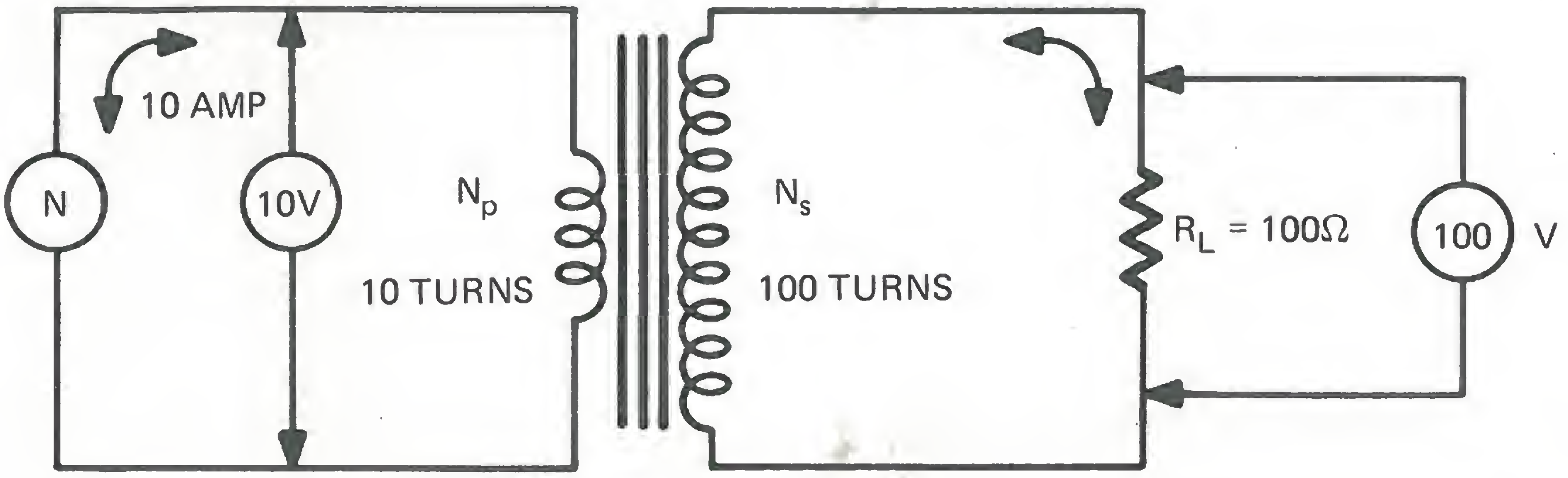


Fig. 12-5 Iron Core Transformer with 10:1 Turns Ratio

The fact that the magnetic core becomes warm or even hot shows that energy is being lost in the form of heat during the energy transferring process. The two main effects of the temperature rise are *eddy-current* and *hysteresis losses.*

The eddy currents represent wasted power dissipated as heat in the core, equal to I^2R where R is the resistance of the core. The higher the frequency of the alternating current in the inductance, the greater the eddy-current loss.

Hysteresis losses occur because of the power needed to reverse the magnetic field in the magnetic materials with the alternating current input. As the frequency is increased, the alternating magnetizing force will no longer be able to magnetize the material completely in either direction. The higher the frequency, the less fully the material will become magnetized.

The heat that is produced in the core of the transformer is the result of the current flowing in the windings. As the current flows through the resistance of the wires, heat is produced. The heat in either winding, in watts, is found by using the formula

$$P = I^2R$$

For this reason, the copper loss is considered the same as the I^2R loss.

With one layer of wire wound over another in a transformer, there is a greater tendency for the heat to remain in the wires than if the wires were separated and air-cooled. Increased temperature causes increased resistance of the windings. As a result it becomes necessary to use heavier wire to reduce resistance and heat loss than would be necessary if the same circuit were exposed to the air.

The ratio of output power to the input power is the *efficiency* of the transformer. The things that determine the efficiency are the copper, eddy current and hysteretic losses. The ratio of output to input is always less than one and is usually given in terms of the percent efficiency. To find the percent efficiency of the transformer use the following equation:

$$\text{Percent Eff.} = \frac{P_o}{P_{in}} \text{X } 100$$

It will be found that power transformers are usually warm to the touch when operating. In some cases it becomes necessary to air-cool transformers to keep them from overheating and damaging the insulation on the wires of the windings. Some transformers are built into oil-filled cases. The oil helps to insulate the internal wiring, preventing moisture from forming on the insulation, which might result in a breakdown. It also carries heat from the windings to the outer case to be dissipated into the air.

Transistors are usually mounted on large metal blocks as shown in figure 12-3. These blocks are known as heat sinks. The metal block gives the transistor a larger mass and surface area. As seen by equation 12.1, the more mass an object has, the greater will be the time it takes to heat up. Also, the larger surface area will have more exposure to air. The more contact with air the heat sink has, the faster the heat will be dissipated.

The same principle applies to transistors as applies to transformers. Power loss goes up with a rise in temperature; therefore, it is advantageous to keep the devices as cool as possible.

MATERIALS

1 Power transformer

1 Thermocouple meter

1 AC motor

1 Cardboard box with insulation material

1 Mercury thermometer 0-200°F optional

1 Variable transformer (0-130V 60 Hz)

1 Timer or watch with second hand (supplied by student)

PROCEDURE

1. Connect the transformer as shown in figure 12-6.

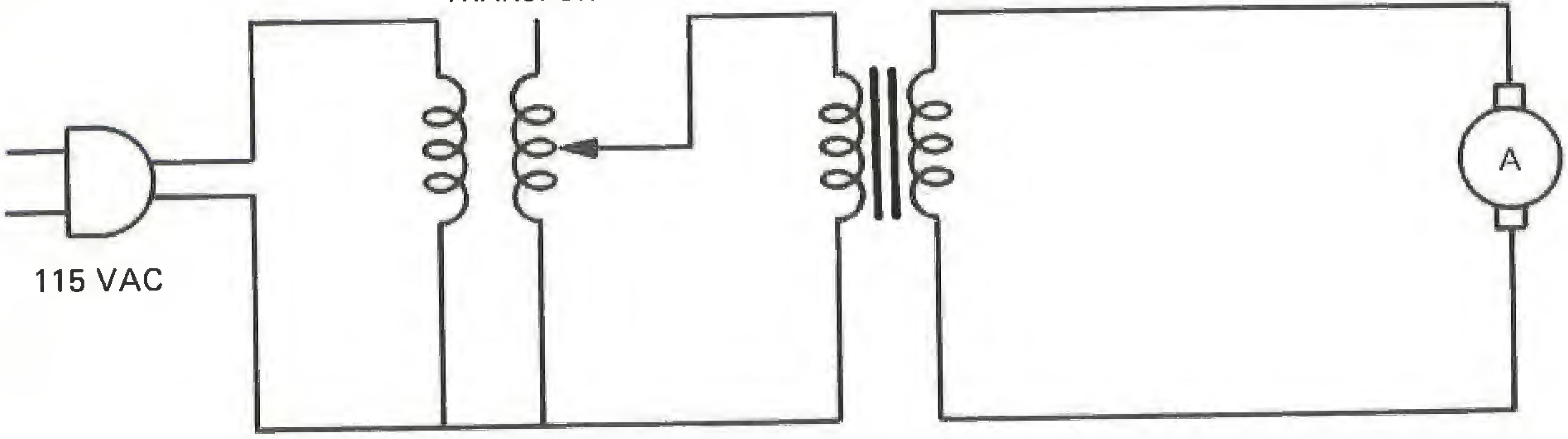


Fig. 12-6 Transformer Circuit

2. Connect the leads from the thermocouple meter to the transformer. If a thermocouple meter is not available, use a sensitive mercury thermometer taped to the case of the transformer.
3. Place the thermometer in a cardboard box and cover with insulating material.
4. Increase the voltage from the Variable transformer until the motor is running.
5. As the transformer heats up the temperature measuring device (whether the thermometer or the thermocouple meter) will indicate the rise in temperature.
6. **Be careful not to heat the transformer to a temperature that will melt the insulation.**
7. **If smoke appears or a burning smell is sensed, disconnect the supply voltage immediately.**
8. After the temperatures have reached their peak value (may have to wait as long as two minutes for the mass to stop increasing in temperature), record the maximum temperature and the time it was recorded in figure 12-7.
9. Start the time recordings immediately after the temperature has reached the maximum value.
10. For the first 10 minutes, record the temperature every 2 minutes as the temperature falls.

Time Max. Temp. Was Reached = ________	Max. Tem. = ________
Time (Min.)	Temp. (Degrees)

Fig. 12-7 Data Table

11. Then record the temperature in 5-minute increments for the next 20 minutes.
12. Continue recording temperatures in 10-minute increments until the room temperature is reached.
13. Accurate results can be found when care is taken in recording the temperatures and time increments.

ANALYSIS GUIDE. Plot a graph of decreasing temperature versus time as the transformer cools down. Determine from the resulting exponential curve, the time constant of this particular transformer. Is this time constant agreeable with what it should be if it is assumed steady-state temperature is reached after 5 time constants?

PROBLEMS

1. If a power transformer having a voltage step-up ratio of 1:6 is placed under load, what will be the approximate ratio of primary to secondary current?
2. A 300 – 16 piece of aluminum whose specific heat is .22 BTU/lb-°F is heated from 70° to 100° F. How much heat did the aluminum absorb?
3. A 1-lb. piece of iron at 212°F is dropped into 1 lb. of water at 32°F. What is the temperature of the iron and water after the temperature of the mixture has had a chance to come to equilibrium? (The specific heat of iron is 0.12 BTU/lb.-F°.)

experiment 13 DC Vs. AC OPERATION OF A SERIES MOTOR

INTRODUCTION. Of all the different types of AC and DC motors, one of the most versatile types is the series *universal motor.* In this experiment we will investigate the operation of the universal motor, using both AC and DC input voltages.

DISCUSSION. A motor which can be operated from either an AC or DC power source is called a universal motor. To understand the way that the universal motor operates, a discussion of both the *series type DC* and *series type AC motor* is in order.

The series DC motor has its field windings connected in series with the armature. Since these windings must carry the same current as the armature, they must be made of relatively few turns of large size wire.

The field windings produce a magnetic field between two pole pieces of highly permeable material in such a manner that a north and south pole are developed within the motor. This arrangement is known as the *stator.*

The *rotor* assembly is made up of a slotted iron core, the armature winding and the commutator assembly. The commutator provides a means by which the current can enter the armature from the power source by way of two carbon brushes.

Direct-current series motors are variable-speed motors with speed varying with load. It is possible to get considerable power on an *intermittent duty* basis from a small frame size with this type of motor. However, the DC series motor should be loaded before a voltage is applied to keep it from overspeeding.

Because the variation of speed with load is so great, the series motor has poor speed regulation. The equation defining speed regulation is

$$\boxed{\%\text{ speed reg.} = \frac{\omega_{NL} - \omega_{FL}}{\omega_{FL}}} \tag{13.1}$$

where ω_{NL} = no-load speed
ω_{FL} = full-load speed

When speed control is used with a series motor, it is provided by inserting resistance into the armature circuit. Small series motors are used in fans, blowers, some inexpensive electric drills, or in any application in which speed regulation is not too important. Their high starting torque makes larger series-type motors useful for heavy-duty jobs in cranes and hoists.

The direction of rotation of the DC series motor can be reversed by reversing either the two leads of the field winding or the two armature leads. Reversing the input leads does not cause a reversal in the motor's rotation.

The characteristics of the series AC motor are similar to those of the DC series motor. The armature is similar in construction to that of the DC motor. However, a *laminated iron core* is used for the field structure in place of the solid field poles of the small DC motor. The laminated core is necessary in order to keep the *eddy-current losses* in the iron core at a reasonable value. The series AC motor has the same hazard of overspeeding under no-load conditions as does the DC motor. Reversal of the rotor is

accomplished by reversing the direction of current flow in either the field or the armature winding.

The series AC motor is made mostly in fractional-horsepower sizes and is usually an integral part of the appliance it is to drive. Common applications are drills, vacuum cleaners, food mixers, etc.

The universal motor is a modification of the DC series motor and it can operate with a *single-phase* AC input. It has its field and armature windings connected in series with the line voltage. The commutator keeps the current flowing in the rotor windings to assure rotation in the desired direction. This motor works well with *low frequency* AC current because when the current shifts polarity, the magnetic field generated by the field shifts as does the current in the rotor winding — resulting in rotation in the same direction.

In AC applications it has the inherent advantage of extremely high speed and starting torque, so it offers the smallest size per output rating of any 60 Hertz AC motor designed. Its limiting factor is very poor speed regulation, although a *governor* can be used to overcome this problem.

High operating temperatures and brush wear usually demand intermittent use such as in fans, blowers, food mixers, portable electric drills, and other applications where a high speed under light loads or a slow speed with high torque is required. The speed torque characteristic curves are the same as those of the series AC and the series DC motors. Figure 13-1 shows these curves.

In DC applications, high starting torque and relatively high speed (a factor that allows much power in a small package) are outstanding features. However, poor speed regulation is still a drawback. It is important to have a small amount of load applied when first starting a universal motor to avoid running the motor at too high a speed.

One of the difficulties with universal motors is a result of *commutator sparking* which results in radio interference, or *noise*. This noise may be reduced by bypassing the two brushes to the frame of the motor with 0.001 to 0.01-μF capacitors and grounding the frame.

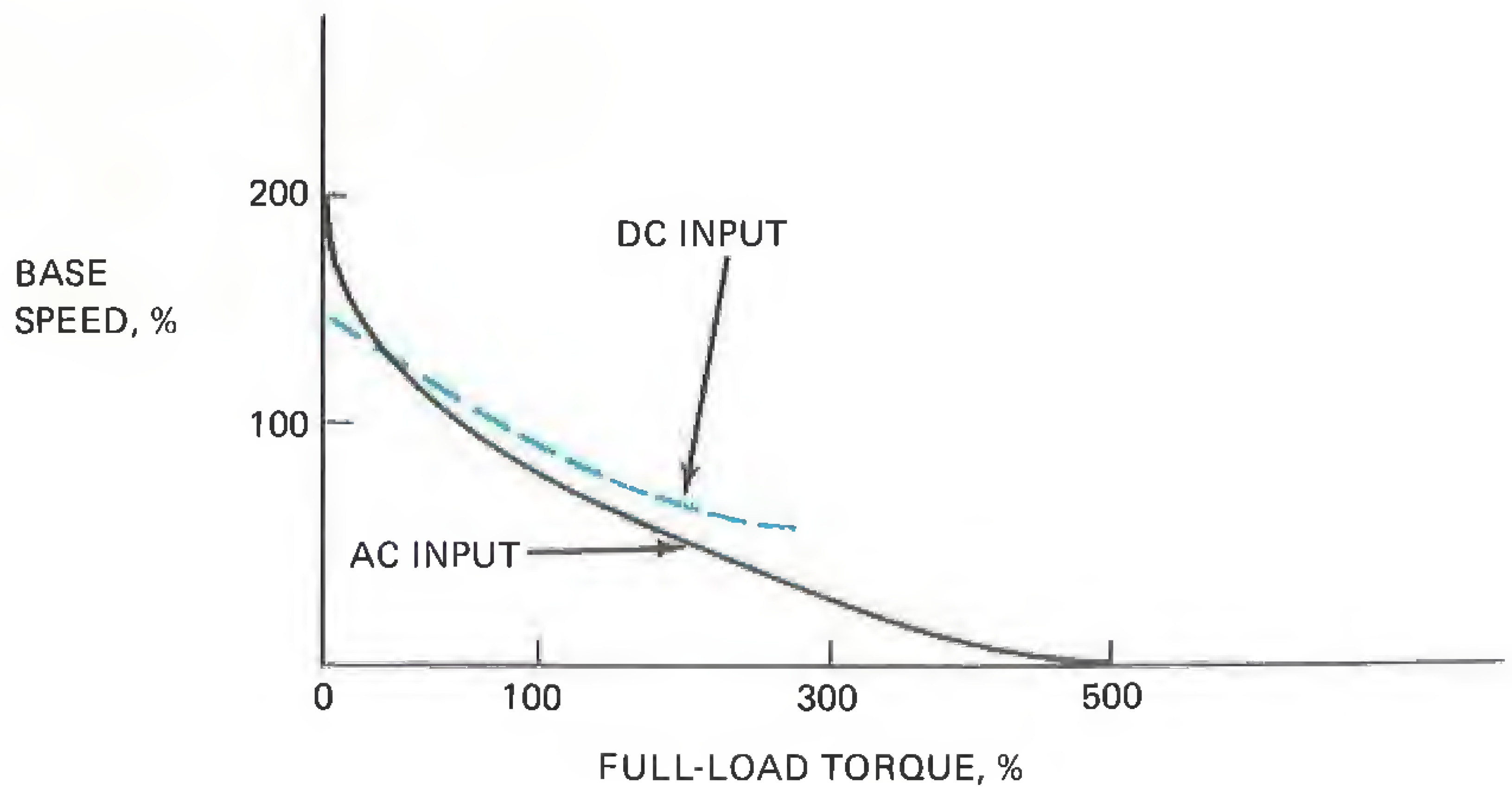


Fig. 13-1 Speed-Torque Characteristic Curves for A Universal Motor

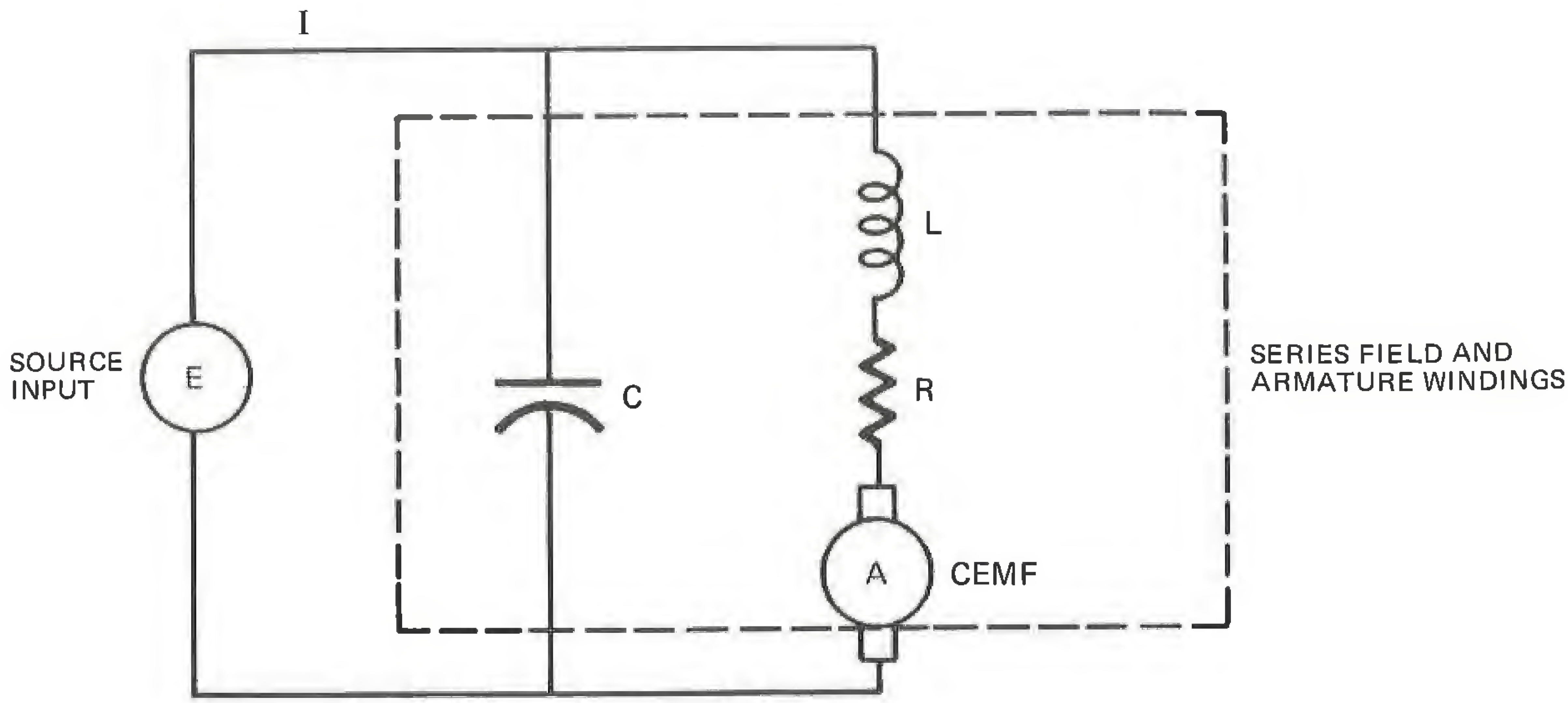


Fig. 13-2 Equivalent Circuit for Universal Motor

The equivalent circuit for a universal motor is given in figure 13-2. The windings in the field and the armature have the combined effects of *capacitance* and *inductance* along with their resistance. When the armature starts to rotate, a voltage will be induced in the armature coils because of their cutting of the magnetic field set up between the poles. The polarity of the induced emf is opposite to the impressed voltage and is called *counter emf.* The counter emf of the motor is produced by the same kind of action that produces the induced emf of a generator and is proportional to the factors given in equation 13.2.

$$\text{cemf} = \frac{2\phi C\omega}{60 \times 10^{-8}} \qquad (13.2)$$

where ϕ = total flux going from north to south pole
C = number of conductors connected in series
ω = speed in RPM

When a DC motor is operating at its normal speed, the counter emf is slightly lower than the impressed voltage. The cemf for a DC motor can be found by

$$\boxed{\text{cemf} = E_{in} - I_a R_a} \qquad (13.3)$$

where E_{in} = impressed voltage, volts
I_a = armature current, amps
R_a = armature resistance, ohms

When the universal motor is operating with a DC input, the equivalent circuit in figure 13-2 changes to look like the one in figure 13-3.

By knowing the input voltage, the cemf, and the effective armature resistance, the value of the armature current can be found by

$$I_a = \frac{E - \text{cemf}}{R} \qquad (13.4)$$

By knowing the armature current, the power delivered by the motor can be expressed as

$$P = I_a^2 R_a \qquad (13.5)$$

or $$P = (E - \text{cemf})\, I_a \qquad (13.6)$$

These equations were developed by using Ohm's Law and the power equation, $P = EI$.

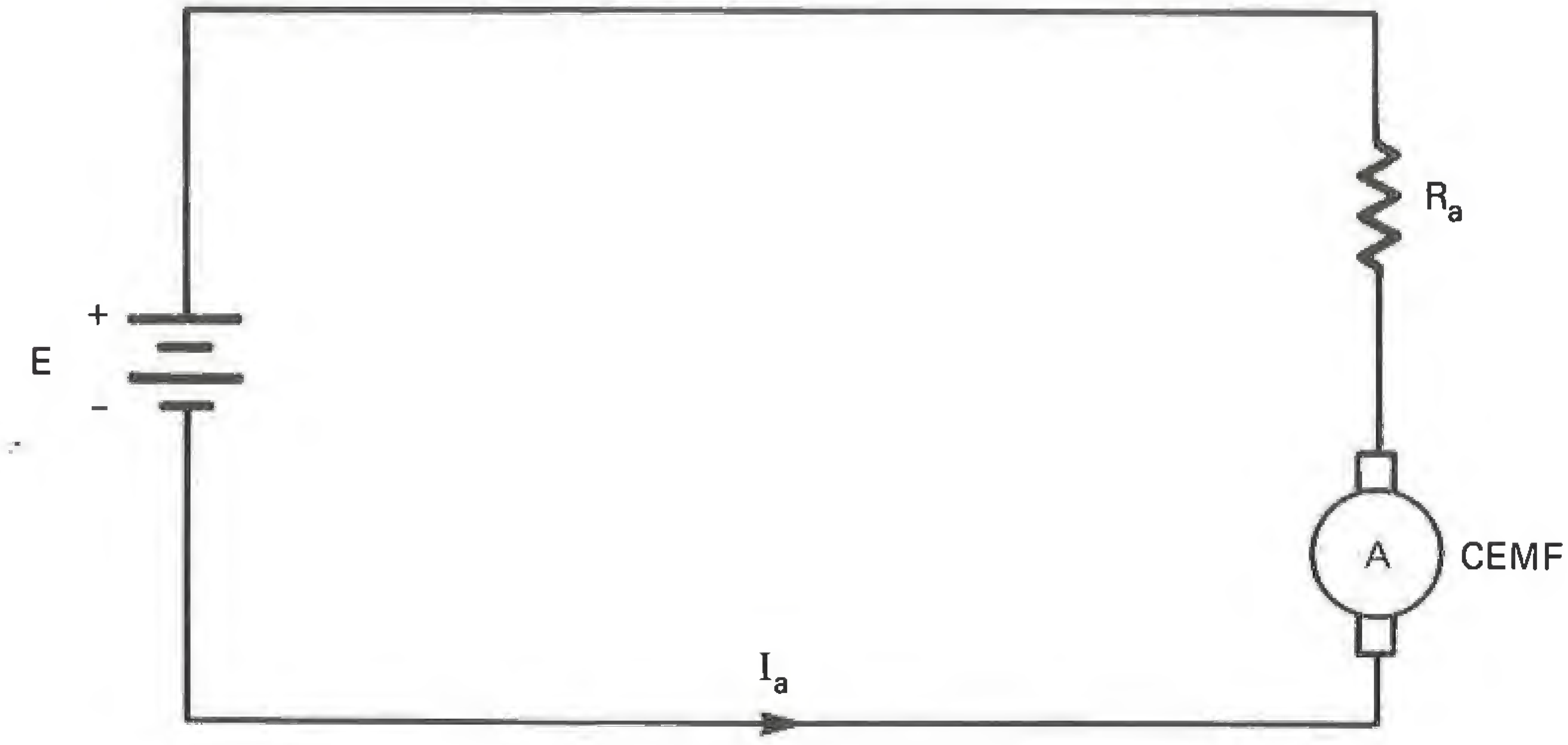


Fig. 13-3 Equivalent Circuit of Universal Motor Operating with DC Input

When the universal motor is operating with an AC input, the equivalent circuit is changed to look like the one in figure 13-4.

The circuit, when operating under AC power, shows the effects of the inductance in the windings as well as the resistance. The reason the inductance is not considered when the motor is operated under a DC source will be obvious when the definition of inductive reactance is considered.

Resistors, inductors, and capacitors all *impede* the flow of alternating current in a circuit. The effect of resistance is to dissipate part of the electrical energy in the form of heat. As with direct current, Ohm's Law can be used in alternating current circuits as well, and

$$I = \frac{V_R}{R}$$

where V_R = voltage drop across the resistor, in volts and R = value of the resistor, ohms.

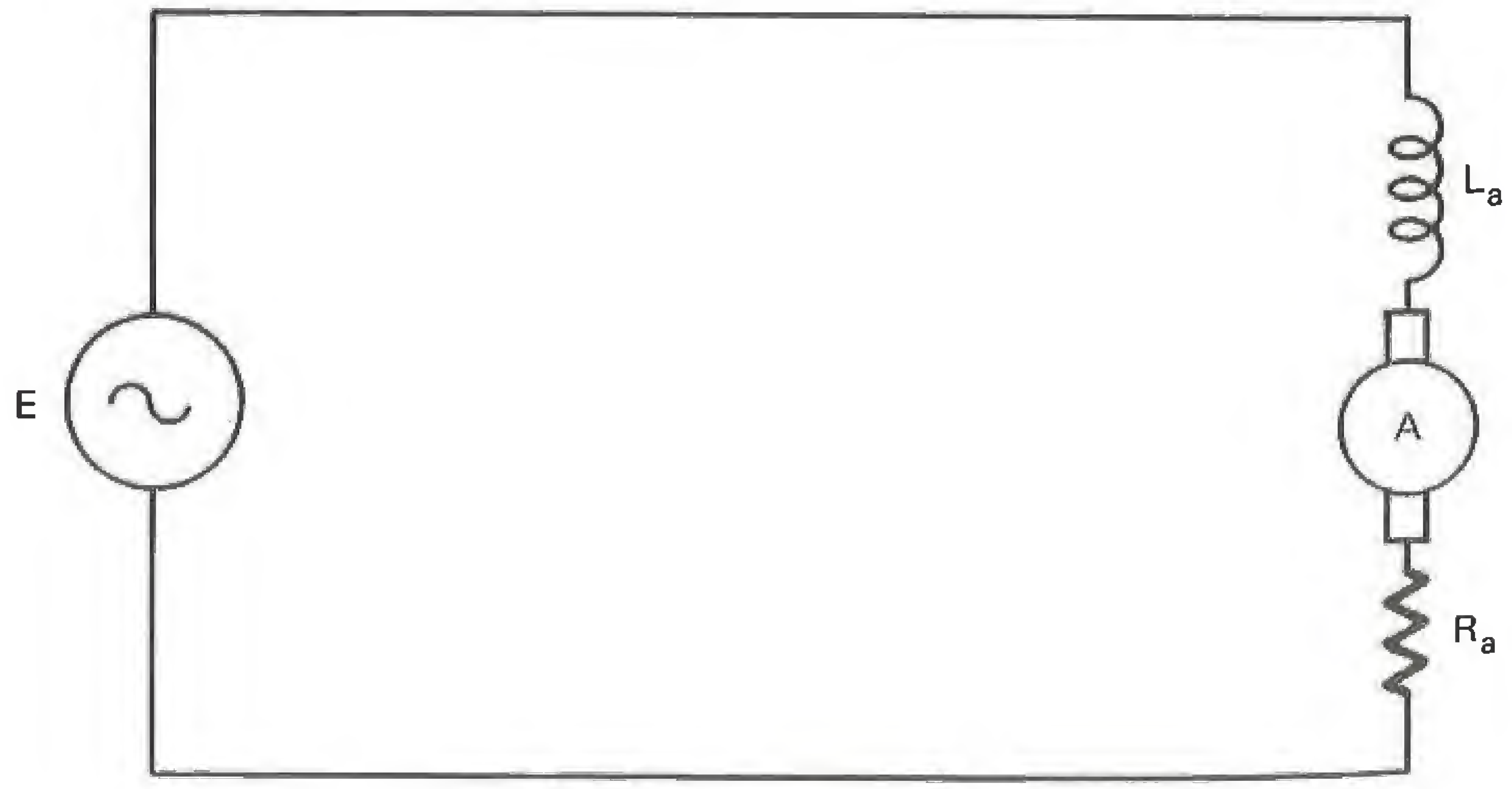


Fig. 13-4 Equivalent Circuit of a Universal Motor Operating with an AC source.

The opposition an inductor offers to the flow of alternating current arises from the self-induced back emf produced in it by the changing current. The counter emf represents a potential drop across the inductor and the current in the circuit is correspondingly reduced. The *inductive reactance* X_L of an inductor is a measure of the effect of the alternating current passing through it. The *effective current* in an inductor is related to the *effective potential difference* V_L across it and the inductive reactance X_L by

$$I = \frac{V_L}{X_L} \qquad (13.7)$$

The unit of inductive reactance is the ohm. Even though equation 13.7 is similar to Ohm's Law, there is a basic difference between resistance and reactance. In an inductor there is no power loss due to reactance, while power is dissipated as heat in a resistor.

The inductive reactance of an inductor is given by the formula

$$X_L = 2\pi fL = \omega L \text{ ohms} \qquad (13.8)$$

where f = frequency of the current in cycles per sec.
L = inductance in Henrys
ω = angular speed, radians per sec.

Because inductive reactance depends upon the frequency of alternation of the current, it is not present in the DC circuit of figure 13-1 since the current does not alternate.

Even though the circuit in figure 13-4 does not show the effects of *capacitive reactance,* it is important to understand this phenomena before the subject of impedance is discussed.

The extent to which a capacitor opposes the flow of alternating current depends upon its capacitive reactance X_C. If V_C is the effective potential difference across a capacitor whose reactance is X_C, the effective current into and out of the capacitor is given by

$$I = \frac{V_C}{X_C}$$

The capacitive reactance is given by

$$X_C = \frac{1}{2\pi fc} = \frac{1}{\omega C} \text{ ohms} \qquad (13.9)$$

where f = frequency of the current in cycles per sec.
C = capacitance in Farads
ω = angular velocity in radians per sec.

A capacitor impedes the flow of alternating current by virtue of the reverse potential difference that appears across it as charges build up on its plates. The inverse dependence of X_C upon f and C follows from the way in which a capacitor responds to alternating current. At high frequency, each cycle is brief, and less charge is deposited on the plates of the capacitor for each cycle; hence, there is smaller opposing potential difference, and more current flows into and out of the capacitor. As the capacitance C increases, X_C decreases; hence, more current can flow in the circuit.

In the DC circuit with f = 0, the values of X_L and X_C are zero and infinity respectively. When the current does not vary, there is no self-induced back emf in an inductor, and no inductive reactance to impede current. The capacitor, however, completely obstructs direct current because the charge that builds up on the plates remains there instead of alternating back and forth as it does when an AC potential is applied.

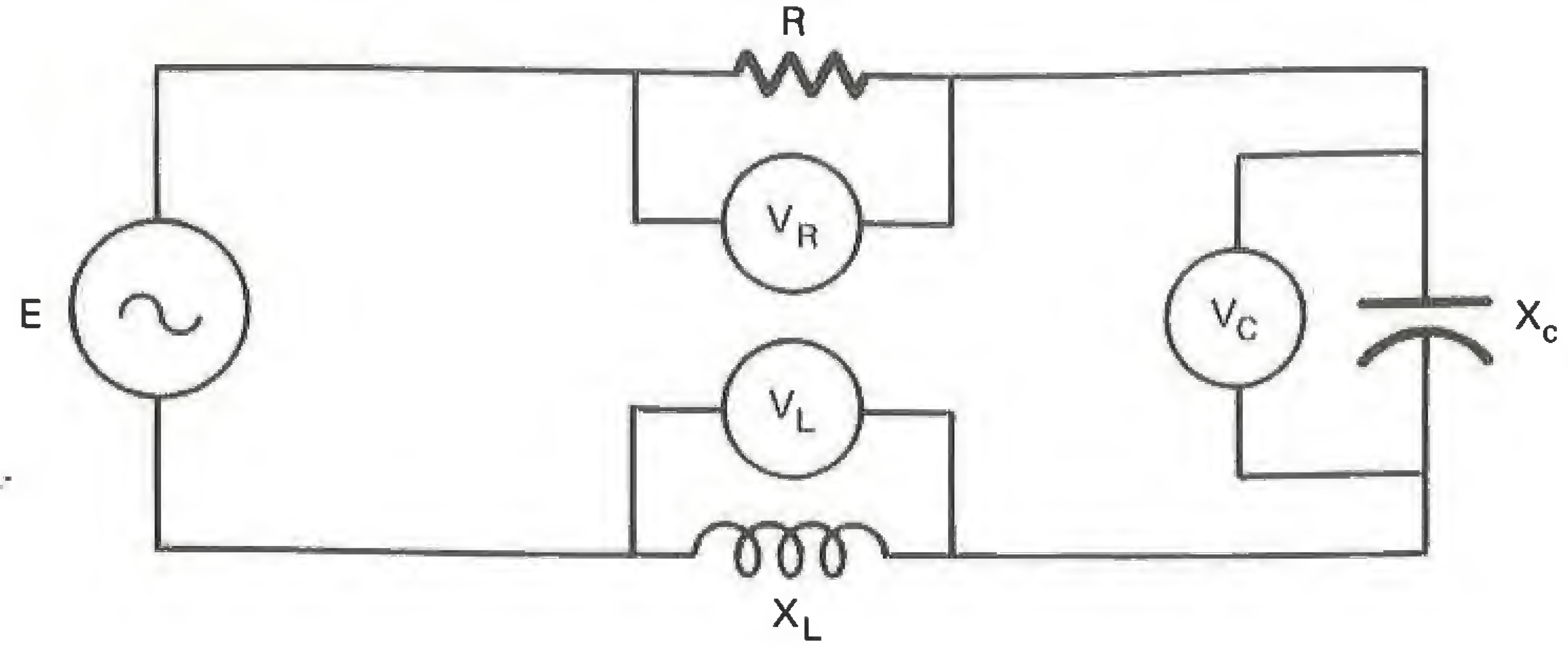


Fig. 13-5 Basic RLC Circuit

A series circuit which has the effects of resistance, capacitance, and inductance is shown in figure 13-5.

If an AC source of emf is connected to the circuit, at any instant in time the applied voltage E is equal to the sum of the voltage drops across the various circuit components:

$$E = V_R + V_C + V_L \qquad (13.9)$$

The voltage V_R is always in phase with the current in the circuit. However, V_C is 1/4 cycle behind I and V_L is 1/4 cycle ahead of I. The corresponding waveforms are shown in figure 13-6.

Equation 13.9 is correct as long as the instantaneous value of the voltage is wanted. When the *effective* or *maximum* values are involved, a vectorial approach has to be used to take into account the *phase difference.*

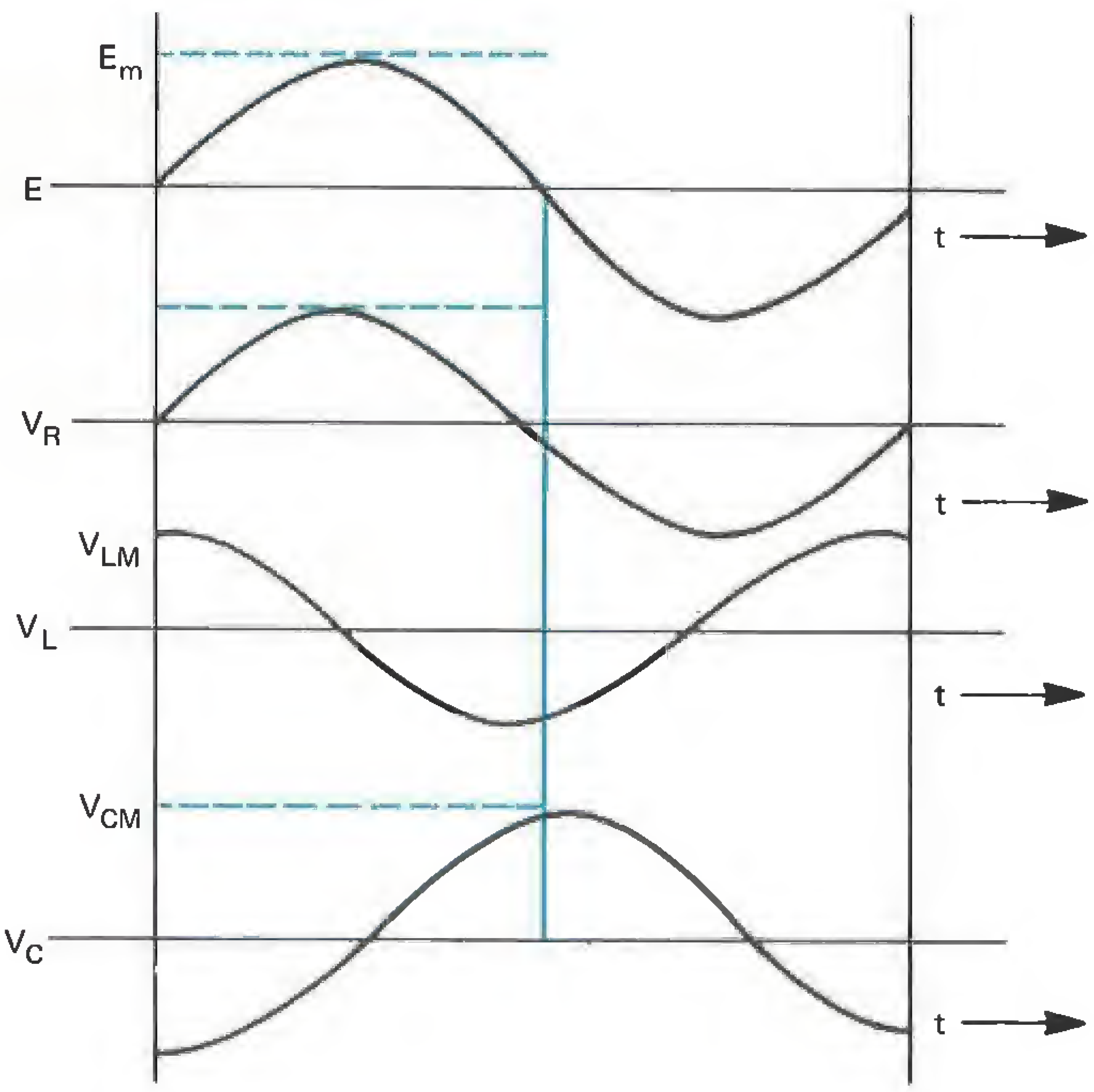


Fig. 13-6 Waveforms for the Circuit in Figure 13-5

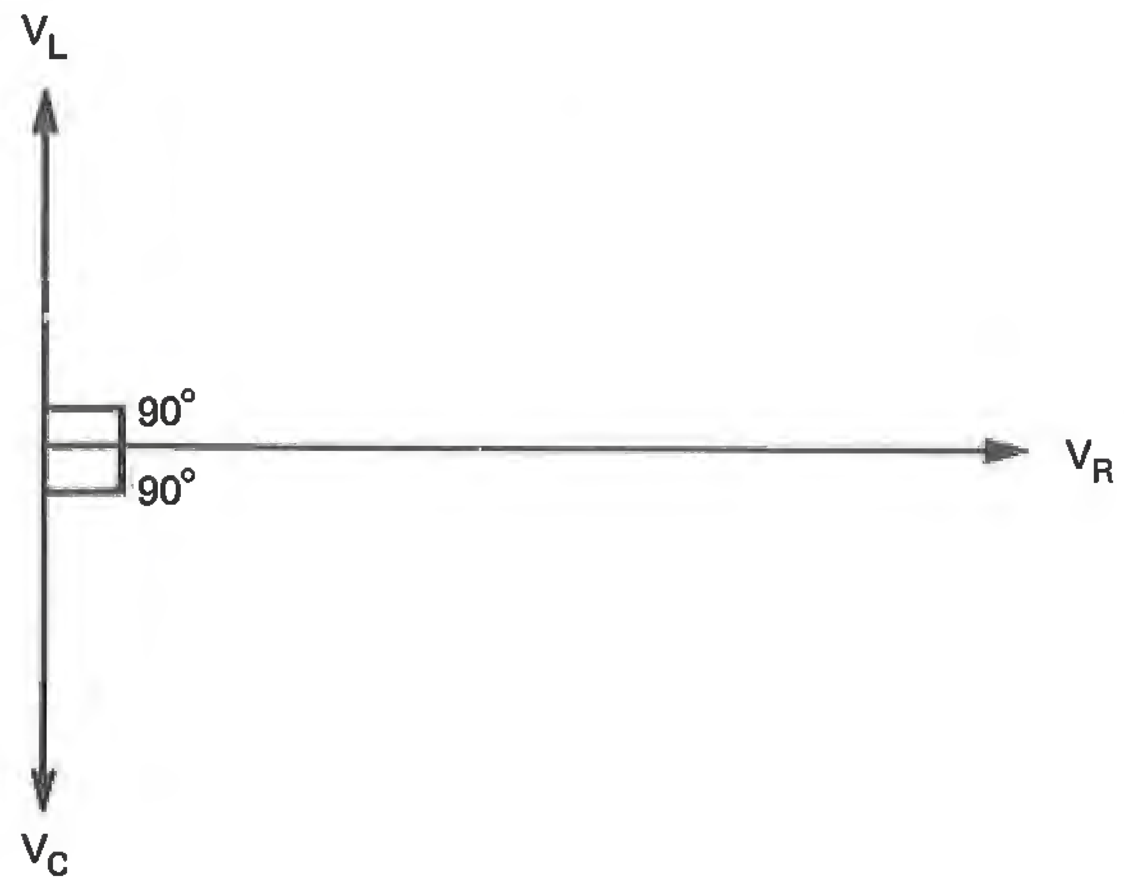


Fig. 13-7 Vector Diagram of Effective Voltages Across the Components in Figure 13-5

Figure 13-7 shows the *polar* diagram used when given the effective values of V_R, V_L and V_C. V_L is drawn in the +y direction, V_C in the -y direction, and V_R in the +x direction.

The vector sum of V_L, V_R, and V_C represents the effective voltage across the terminals of the circuit and is given by

$$E = V_R + jV_L - jV_c \qquad \textbf{(13.10)}$$

where V = effective voltage across the terminals. The angle ϕ between E and V_R is called the phase angle and indicates how much the current in the circuit *leads* or *lags* the voltage.

Because

$$V_R = IR,\ V_L = IX_L,\ \text{and}\ V_C = IX_c$$

equation 13.10 can be expressed in the form

$$E = I(R + jX_L - jX_c).$$

The quantity

$$(R + jX_L - jX_c)$$

is known as the impedance, Ƶ, of the series circuit. The unit of impedance is the ohm. Impedance in an AC circuit plays a similar role to that of resistance in the DC circuit. Therefore,

I = E ÷ Ƶ for an AC circuit.

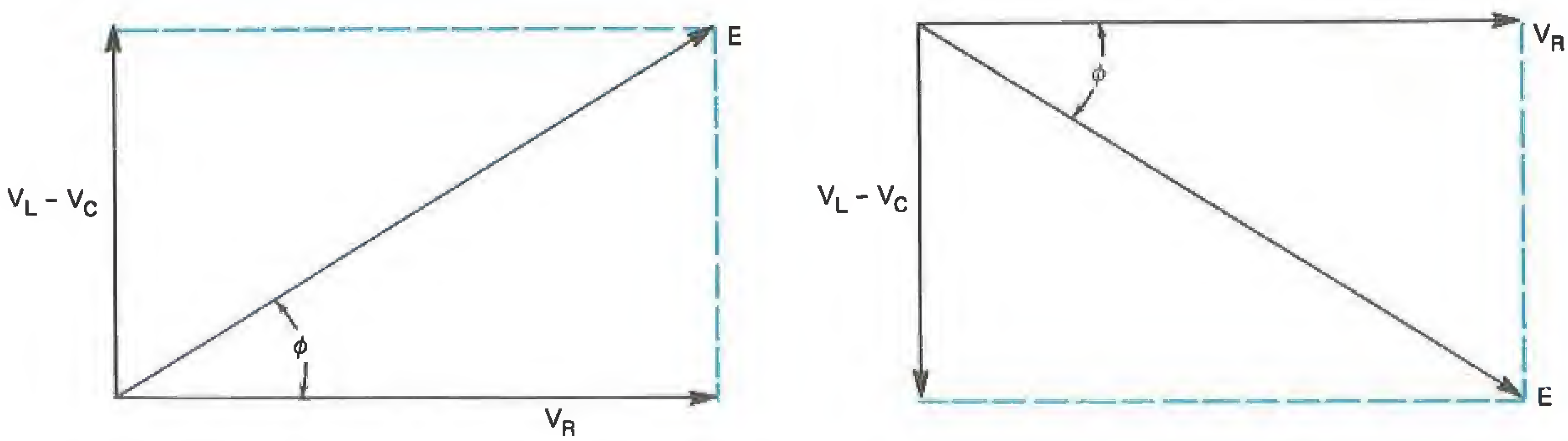


Fig. 13-8 Vector Diagrams for $V_L > V_C$ and $V_C > V_L$

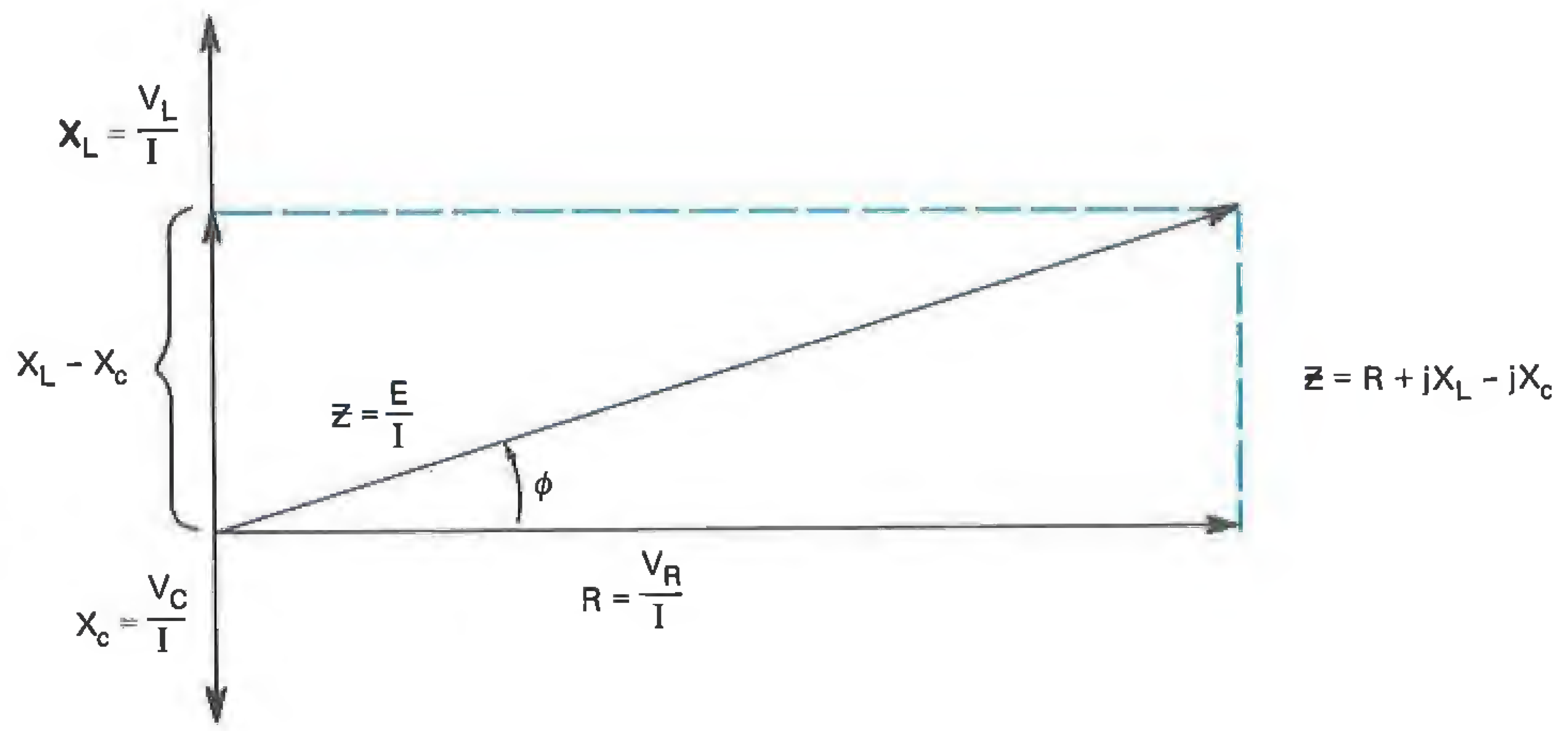


Fig. 13-9 Impedance Diagram

Because the current I is the same in all parts of the circuit at the same time, the vector voltage diagram can be replaced by a vector impedance diagram as shown in figure 13-9.

The phase angle ϕ is not changed and can be found from the relationship

$$\tan \phi = \frac{X_L - X_c}{R}$$

With the preceding discussion in mind, an expression for the power can be developed for the AC circuit in figure 13-4.

Since $I = \frac{E}{Z}$

then the power delivered into the motor is equal to

$$P_R = I^2 R = \frac{E^2}{Z^2} R$$

where P_R is considered to be the *real power* delivered to the motor.

The *apparent power* delivered to the motor is equal to the product of the voltage and current in the circuit,

$$P_a = EI.$$

The relationship between real power and apparent power is given by the triangle as shown in figure 13-10.

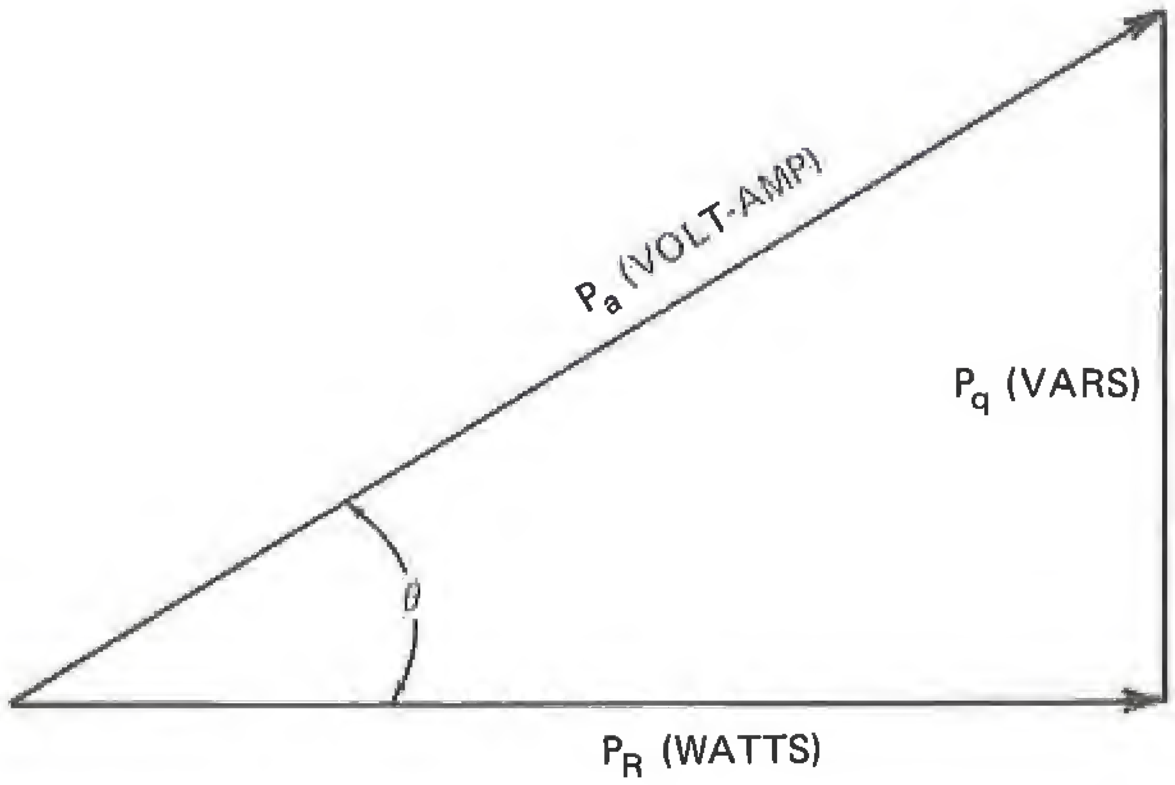


Fig. 13-10 Power Triangle

The triangle is commonly known as a *power triangle* and the angle θ is equal to the power factor angle. The power factor is defined as

$$pf = \cos \theta = \frac{P_R}{P_a} \quad (13.11)$$

or

$$\theta = \text{arc tan} \frac{X_L}{R} \quad (13.12)$$

where equation 13.11 is used with the power triangle and equation 13.12 is used with the polar diagram.

The reason that the triangle in figure 13-10 is used is because the apparent power that a generator supplies to a reactive load is always greater than the true power that the load can convert into some other form of energy. The hypotenuse of the right triangle is greater than either of its sides.

An inductive load, such as a motor, has a lagging power factor and a capacitive load has a leading power factor. Since the true power can not be greater than the apparent power, the power factor cannot have a value greater than one.

The product of the effective voltage and current in a pure inductance is called the *reactive power* of the inductor. The letter symbol for reactive power is P_q where

$$P_q = V_L I_L \text{ in vars.}$$

The reactive power makes up the third side of the power triangle.

In this experiment the cemf of the motor will not be measured. Instead, the resistance of the armature times the current squared will be used as a close approximation to the input power. With increased voltages and current, this value would not be very accurate because of the changes that take place in the resistance of the brush contacts, etc.

MATERIALS

- 1 Dynamometer
- 1 VOM
- 1 AC ammeter
- 1 Wattmeter
- 1 Series motor
- 1 Variable transformer (0-130V 60 Hz)
- 1 DC power supply with voltage and current meters
- Appropriate couplings and motor mounts as needed

PROCEDURE

1. Connect the motor to the dynamometer with the appropriate couplings and motor mounts. It is very important that all fittings are tight and the shafts are aligned accurately.
2. Connect the DC power supply to the motor.
3. Slowly increase the voltage and at the same time increase the load until the loaded motor is running approximately 2200 RPM and the voltage is about half the rated value. It is important to load the motor because it will tend to overspeed and may damage its components.
4. Record the RPM, force, input voltage and input current in the data table, figure 13-11.
5. Leaving the supply voltage constant, increase the load until the RPM decreases 200 RPM.
6. Record the values in the data table.
7. Repeat steps 5 and 6 until the motor stalls.
8. Turn off the supply voltage and decrease the load.

Voltage	Force	Torque	Speed	Current	P_{in}	P_{out}	Efficiency
50							
50							
50							
50							
50							
60							
60							
60							
60							
60							
60							
60							

Fig. 13-11 Characteristics for DC Operation Data Table

9. After the motor and dynamometer cool down, repeat step 3 but increase the voltage about 10% over the value used previously.
10. Repeat steps 3 through 8.
11. Rearrange the supply voltage to look like figure 13-12.

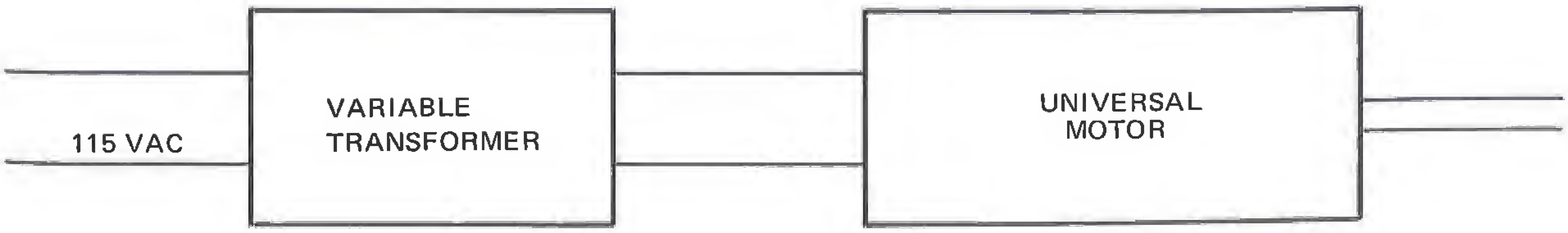


Fig. 13-12 Experimental Set-Up for AC Input

12. Increase the supply voltage to the value used initially, while increasing the load until the RPM is 2200.
13. Record the RPM, the force, input watts, amps, and power factor in the data table, figure 13-13.
14. Increase the load until the speed drops 100 RPM. Be sure the voltage remains the same.
15. Record the quantities from step 13 in the data table.
16. Repeat steps 14 and 15 until the motor stalls. **Be careful of overheating.**
17. Repeat the AC part of the experiment for a voltage value about 10% higher.
18. After the motor has cooled measure the DC resistance of the windings. ______________ Ω.
19. Calculate the torque of the motor by using the equation, torque is equal to force times the radius. The radius arm will have to be measured.
20. Calculate the power into the DC motor using $P_{in} = I^2R$ for each value of load applied.
21. Calculate the mechanical power output for the AC and DC operating conditions.
22. Determine the efficiency for both the AC and DC operation.

ANALYSIS GUIDE. Using the data obtained, plot graphs of the following characteristics on the same sheet of graph paper:

Torque versus speed	DC and AC
Current versus torque	DC and AC
Power in versus efficiency	DC and AC
Power Factor versus current	AC only

From the graphs it should be apparent that the motor runs more efficiently with one of the inputs than it does with the other. Determine the more efficient input voltage and explain why it is more efficient.

PROBLEMS

1. What is the inductive reactance of a pure inductance which allows a 5-amp current to flow when it is connected across a 117-V AC source?
2. At what frequency will the reactance of a 640-μH coil equal that of a 800-μμF capacitor?
3. What is the total impedance at 60 Hertz of a series circuit consisting of a 0.5-Henry inductor with a 200-ohm resistance and a 30-μF capacitor?

Volts	Force	Torque	Speed	Current	Watts	P_{out}	Power Factor	Eff.
50								
50								
50								
50								
50								
50								
50								
50								
50								
50								
50								
50								
60								
60								
60								
60								
60								
60								
60								
60								
60								
60								

Fig. 13-13 Characteristics for AC Operation
Data Table II

experiment 14 AC Vs. DC RELAY OPERATION

INTRODUCTION. A relay is an electromechanical device which is used to control the operation of components in an electric circuit. In this experiment we will investigate the effects of operating a relay with both AC and DC inputs.

DISCUSSION. A relay is an electrically operated switch. The two basic criteria in selecting a relay for a particular purpose are the power source that is available to activate the relay and the switching operation that is to be performed. The first one determines the design of the coil and magnetic circuit, while the other determines the number, type, and arrangement of the contacts. There are, of course, other auxiliary specifications to be satisfied, such as size and weight, expected operating life, liability to failure, insulation, resistance to shock and vibration, cost, etc.

When functioning in communications, general signaling, protection, and control circuits, relays are generally operated by relatively low currents. They may also operate from the output of *electronic devices, photo-electric cells, thermocouples,* etc. Higher current can be used to operate relays where the application calls for them.

Relays are available in many forms, with contact arrangements ranging from a single pair, to stacks of dozens of pairs to handle a large number of independent circuits. The four most often used contact groups are shown in figure 14-1.

Successful establishment of the circuit demands that the contacts close cleanly with minimum *bounce* or *chatter,* and that they be sufficiently large, of the correct material, and activated with sufficient force to prevent *welding* or *arcing* with the initial value of current. Certain types of loads, especially motors, capacitors and some heaters, require a high initial current that later drops to a much lower value. In such cases the initial, rather than the steady-state current, determines the choice of contacts.

Successful interruption of the circuit demands that the contacts open cleanly,

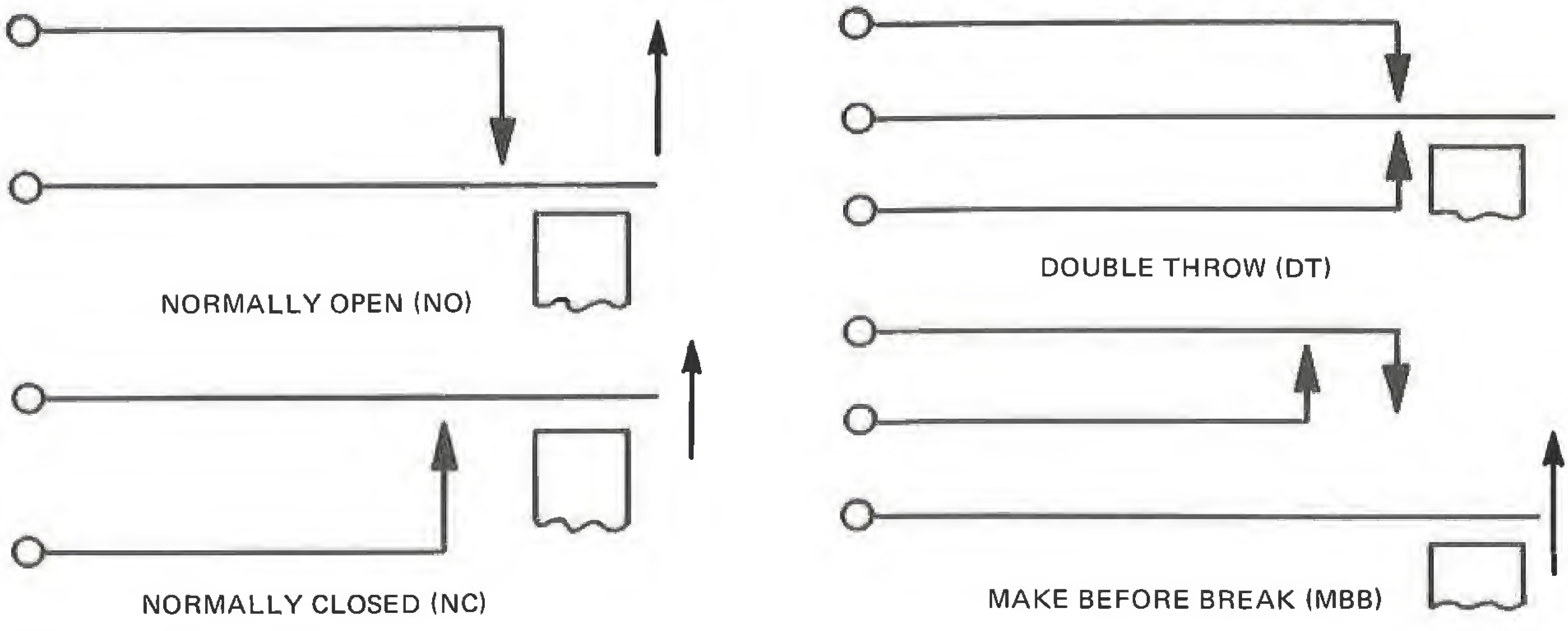


Fig. 14-1 Basic Relay Contact Groups

rapidly, and widely enough to extinguish the arc that always forms on breaking a circuit. High speed of separation without momentary re-establishment of the circuit, and wide separation of the opened contacts permit the interruption of larger currents.

There is no general agreement on the amount of current that can safely be handled by a given pair of contacts. Some rough estimates have been made, however, by the various manufacturers. Silver contacts used in the low-power relays are good for currents up to about three or four amps in the 1/8-in. size, five or six amps in the 3/16-in. size. Double-break contacts will handle about 50 percent more current than single break. This is true for 115-volt 60 Hz AC, for DC voltages up to 32 volts, and for noninductive loads without excessive inrush currents. For 110 volts DC, the current rating should be halved from that of 110 volt AC.

For contact materials other than silver, palladium will carry two or three times the current at the same voltages. Platinum-iridium has about the same current-carrying capacity as palladium, but its great hardness gives a much longer contact life under severe mechanical operating conditions. Tungsten contacts will handle only about 75 to 100 percent of the current of silver contacts of the same diameter, but will do so at two or three times the voltage.

The ideal contact material should have high *electrical* and *thermal conductivity,* high *melting* and *vaporization temperatures,* and *resistance* to *mechanical wear.* Also, the materials should have no tendency to form an oxide or tarnish film which will act as a resistance to the flow of current. High thermal conductivity aids in carrying heat away from the point of contact.

Low-voltage contacts are particularly susceptible to failures because the voltage may not be sufficient to break down any nonconducting film or dust between contacts. When this is not possible to overcome, it is desirable to mount relays with the contacts in a vertical plane to minimize the tendency for dust to accumulate.

High speed of contact operation is desirable because it reduces the duration of the arc and thereby decreases the heating of the contacts. Most relay contacts rebound and reopen their contacts once or several times during the process of opening and closing. Contact bounce reduces contact life and may cause fusing of contacts, especially if contacts are reopened at a time when the current may be several times its steady-state value.

Certain special forms of contacts are sometimes used for especially severe operating conditions. There is a range of coil voltage in which the contact pressure is insufficient to maintain proper contact due to vibration and other causes. To overcome this, snap-action switches such as microswitches are often used. For high-voltage operation, especially at high altitudes, *vacuum contacts* are frequently used. Both mercury and vacuum contacts are useful for operation in an explosive atmosphere. Mercury contacts are susceptible to disturbances from vibration and shock and must be mounted in fixed position.

Most alternating-current relays require a *shading coil* in the pole face to minimize armature chatter and hum. Also, most AC relays use laminated cores to reduce eddy-current heating. Some small AC relays do not use laminated cores.

Since the magnetic materials used in most DC relays contain considerable *residual magnetism,* they require a minimum air gap to

prevent the armature from sticking to the pole face when the current is reduced to zero. This space is usually provided by a non-magnetic screw in the armature opposite the pole face to adjust the residual gap. For high-sensitivity relays where the air gap must be kept to a minimum, it is necessary to use materials such as permalloy which have very low residual magnetism.

The maximum continuous power input to a given relay coil is limited only by the maximum temperature that the coil insulation can withstand without breakdown. The temperature is dependent on the coil construction, the nature of the insulating material, and the conditions of operation.

A number of factors must be considered when deciding on the maximum operating temperature. A relay in an expendable device, such as a bomb, could be allowed to run at a temperature that would cause charring and breakdown in a few minutes. On the other hand, a relay for an industrial control application or one used in an unattended device, such as an automatic lighthouse or weather transmitter, would have to run at a low power input to avoid eventual failure. In humid conditions, a high temperature will help dry out the coil, although the danger of *electrolytic corrosion* of the windings may be present. The maximum temperature is approximately 200°F, although there are new high-temperature insulations now being used which help raise this temperature.

Alternating-current relays usually run somewhat hotter than DC relays of the same types because they are less power-sensitive and because of the eddy-current and hysteretic heating losses which help raise the temperature.

The actual power requirements to operate small relays vary from a few milliwatts to about four watts. Larger relays require up to eight watts.

Because of the increase of inductance with the shortening of the air gap, the AC coil current with the armature closed is usually about 60 percent of that with it open. The inductance of the usual small 110-volt relay with the armature closed is of the order of a few Henrys.

The operating current of a given relay is determined by the length of the open airgap, the rising magnetization current of the iron with the open airgap, and the spring-restoring force on the armature. The release current is determined by the length of the closed gap, the falling magnetization curve of the iron with the closed gap, and the spring force. To make the release current approach the operating current, the ratio of open-gap to closed-gap lengths must be approximately one, and the residual magnetism in the iron must be reduced to a minimum.

In ideal relay operations, the pressure on the normally closed contacts remains constant until the coil current reaches the particular value needed to transfer the movable contacts from the normally closed position to the normally open position with full pressure immediately applied to them. On release, the same operation takes place in reverse order. In actual practice, however, these conditions are not attainable. Usually there is a range of currents near the operating and releasing points where the contact pressure becomes very small and contact continuity becomes erratic, especially under vibration and shock.

Relay	**Average Contact Rating**				**Maximum Coil Voltage**		**Average Coil Power Consumption**	
	AC – 60 Hz		DC					
Type	Amp	Volt	Amp	Volt	AC	DC	AC	DC
Single break	25	24	25	24				
	15	440	1	250	440	230	8	4
Double break	30	24	30	24				
	20	440	2.5	250	440	230	8	4
Metal base	4-6	24	4	24	230	115	4	2
Special base	10-20	125	10-20	24	230	115	4	2

Fig. 14-2 Typical Characteristics of Magnetic Relays

The table in figure 14-2 shows some electrical characteristics of typical magnetic relays.

Relays vary widely in the time needed to operate, but the speed of magnetic relays, excluding timing relays, is relatively fast. The response time varies from about five to 70 millisec with AC power depending on relay size. The average closing speed of a typical AC heavy duty relay is 1-1/2 to 3 cycles, or 25 to 50 millisec on 60 Hertz current, which is considerably faster than the operation of most control devices with which they are used.

Operating speed is determined by the rate of flux buildup combined with the armature closing time. Usually DC relays are slower in operation than AC relays. Without using a special magnet frame or core, relay operating speed can be changed by varying the spring tension, the armature-core gap, and the coil inductance.

One way of speeding up the response time of a DC relay would be to operate it with a voltage several times larger than its rated voltage, with a capacitor to store enough energy to kick the relay closed, and a resistor in series with the power supply to limit the coil current. However, the capacitor used needs to be fairly large. Increasing the number of contact springs on the relay increases the operating time and decreases the release time.

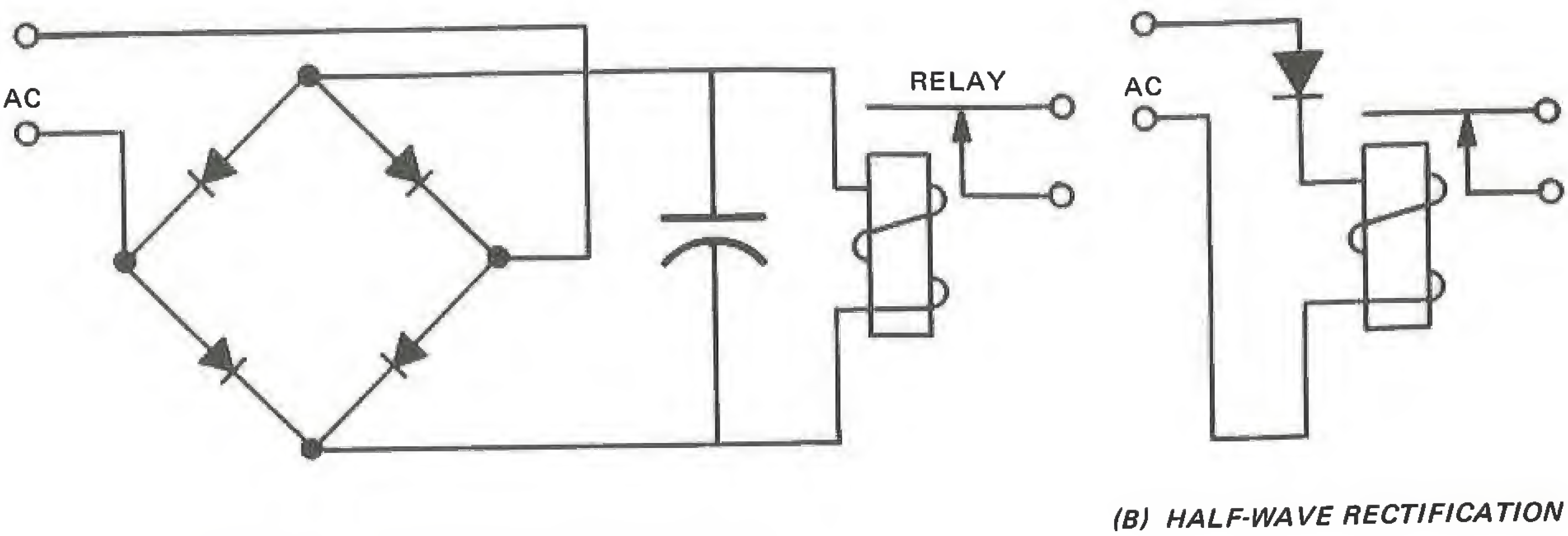


Fig. 14-3 DC Relays Operating with AC Power Source

If a DC relay is used with AC power, the following two circuits, figure 14-3, can be used to convert AC to DC inputs.

The equivalent circuit for the AC relay is given in figure 14-4. The resistor and inductor shown in the circuit represent the resistance and the inductance present within the coil windings. When alternating current flows in the inductance, the amount of current is much less than the resistance alone would allow. The additional opposition to the sine-wave alternating current, resulting from the self-induced voltage across the inductance, is called the *inductive reactance* X_L.

The inductive reactance is found by

$$X_L = 2\pi fL \qquad \textbf{(14.1)}$$

where f = frequency of alternating current in Hertz

L = inductance in Henrys

As the frequency or the inductance increases, the value of the inductive reactance increases. Since the frequency of direct current is zero, there is no inductive reactance in a relay operating under a DC supply. The only opposition to the current in the DC relay is the resistance of the windings themselves. Figure 14-5 shows the equivalent circuit for a relay.

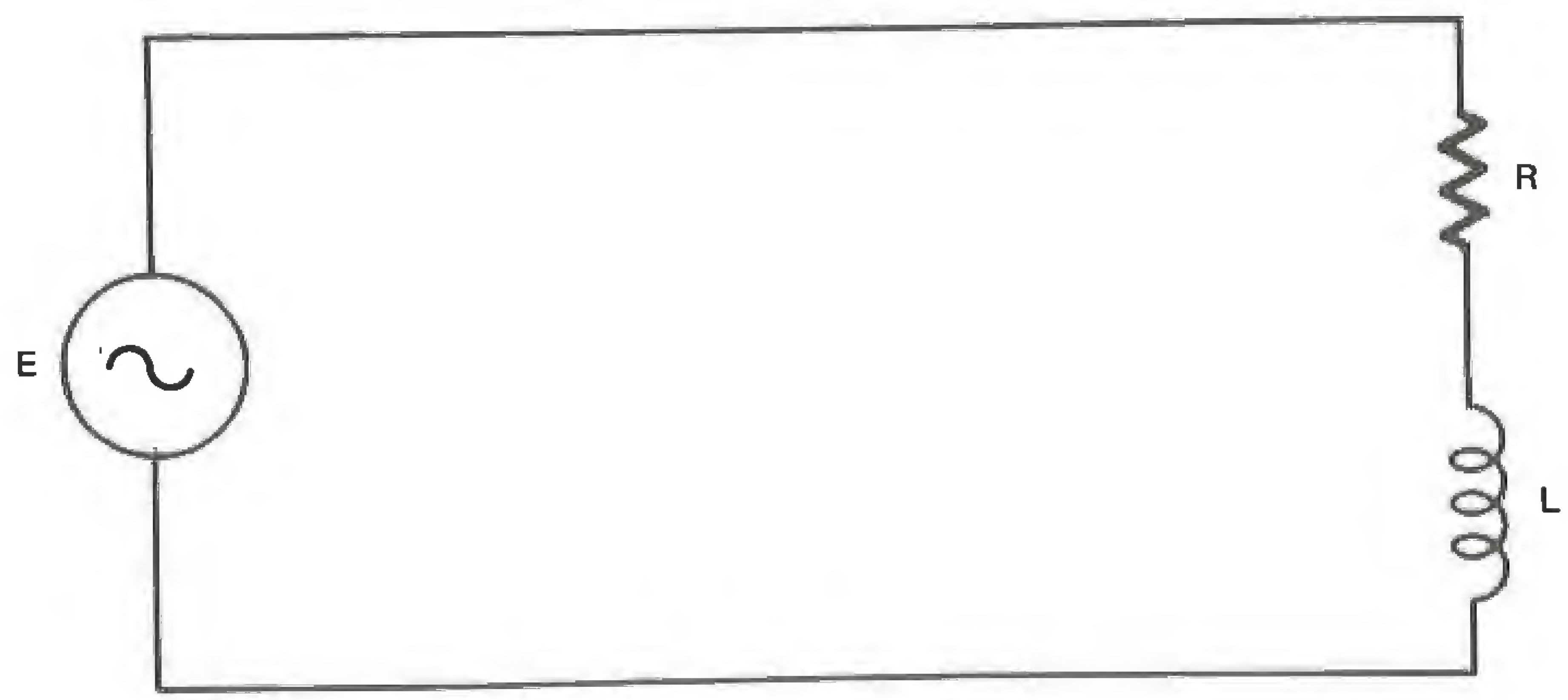


Fig. 14-4 Equivalent Circuit for an AC Relay

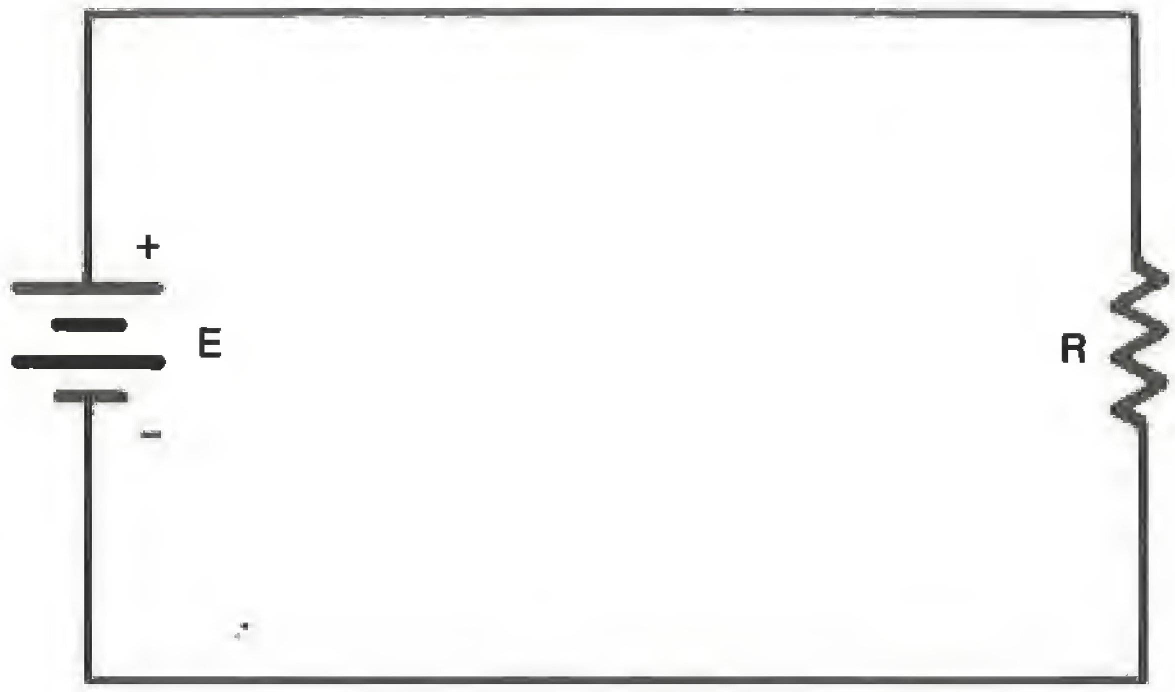


Fig. 14-5 Equivalent Circuit – DC Relay

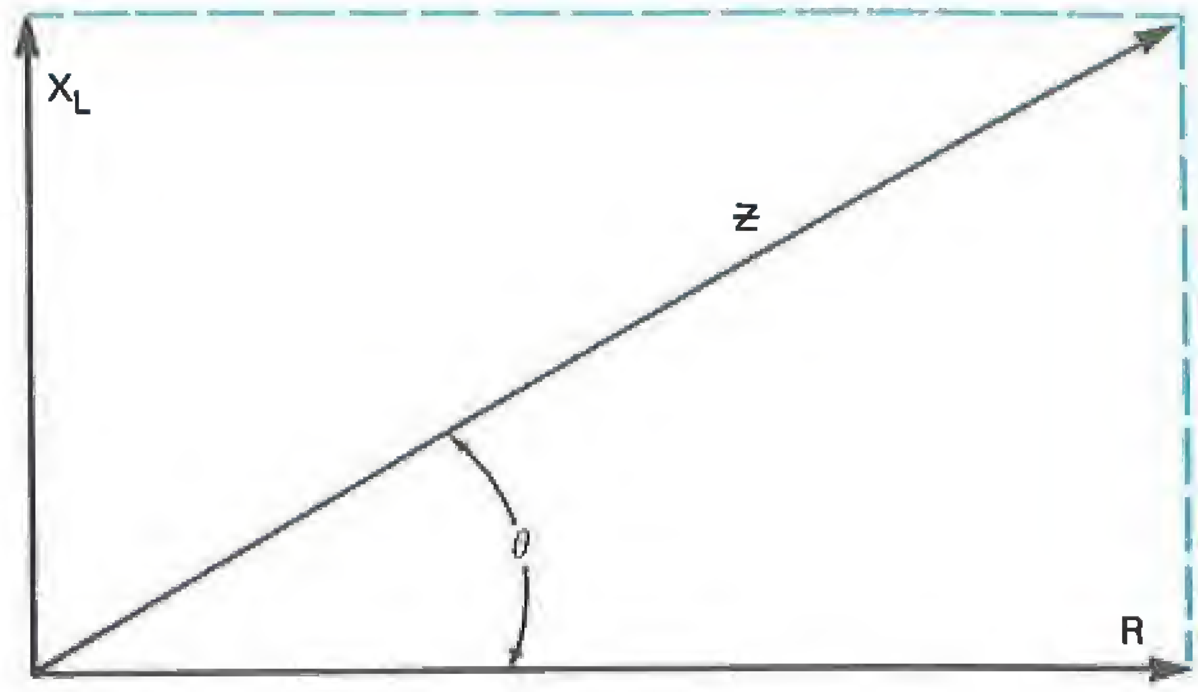


Fig. 14-6 Phasor Diagram – Impedance

The total opposition to current flow in the AC circuit is known as *impedance.* The impedance for the circuit shown in figure 14-4 is equal to

$$Z = R + jX_L \tag{14.2}$$

The phasor diagram describing equation 14.2 is given in figure 14-6.

The angle θ represents the angle at which the voltage across the inductor leads the current through the resistor. This angle is known as the *phase angle.* If sine waves of the voltage and current were plotted against angular degrees, the voltage across the resistor would lag behind the inductor's voltage by the angle θ because the voltage across the resistor is always in-phase with the current in the circuit.

The current in the AC circuit is

$$I = \frac{E}{Z} \tag{14.3}$$

The *apparent power* delivered to the inductor is equal to the product of the AC voltage and current in the circuit

$$P_a = EI$$

The *real power* delivered into the inductor is equal to

$$P_R = I^2R$$

where R is the DC resistance of the windings.

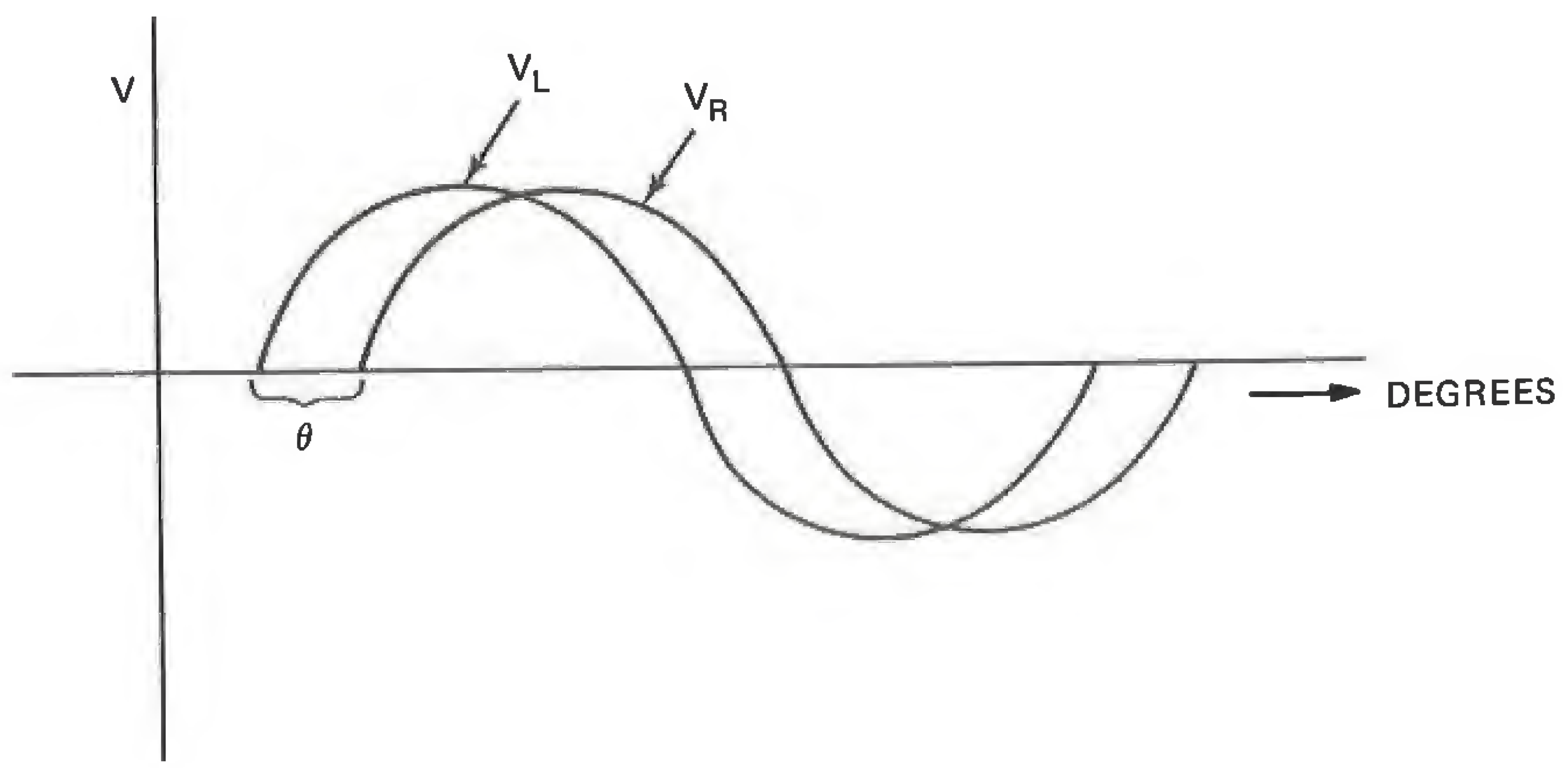


Fig. 14-7 Voltage Waveforms in an RL Circuit

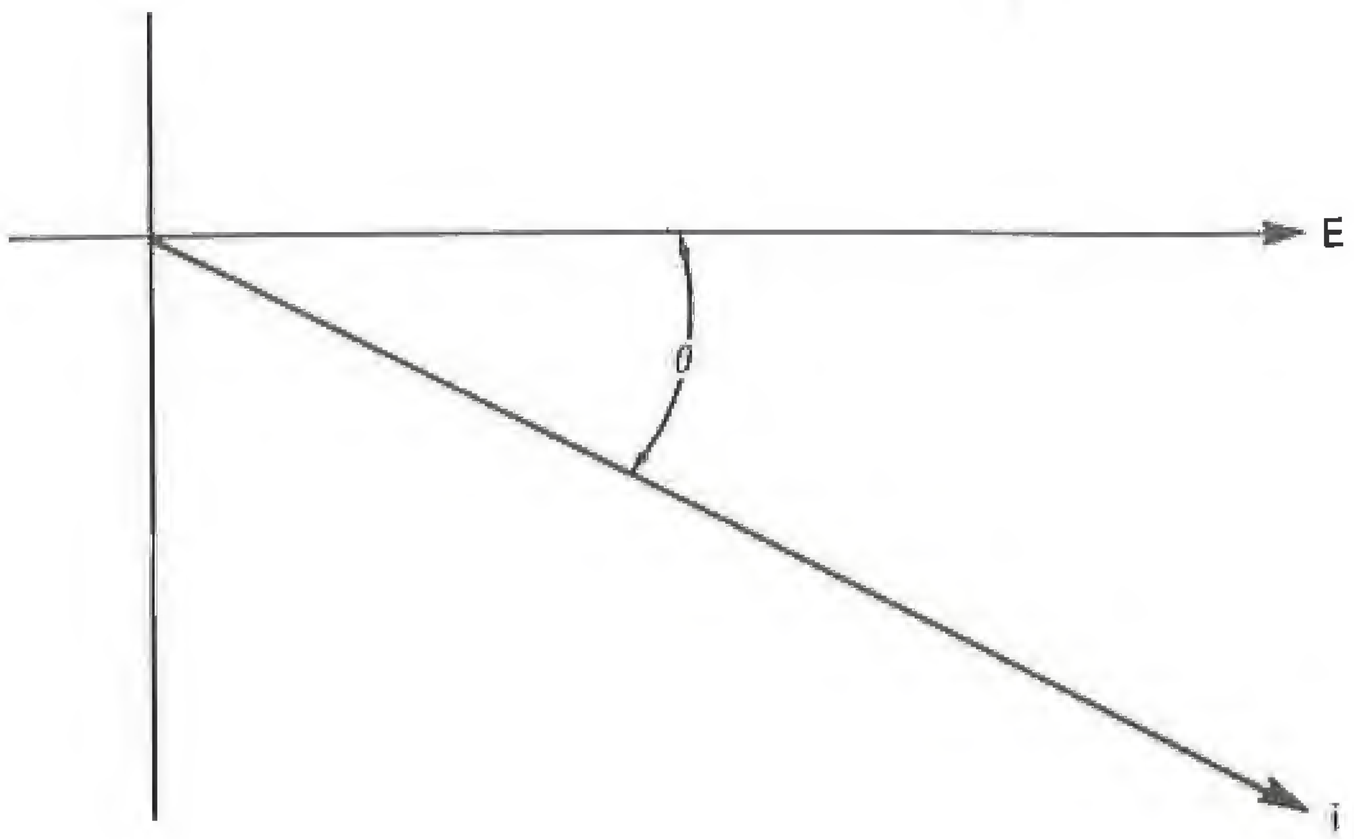


Fig. 14-8 Phasor Diagram for RL Circuit

These equations are derived using the following approach: Using the voltage E as a reference and the current I lagging by an angle θ, the polar diagram would look like the one in figure 14-8.

The current I is equal to

$$I = \frac{E}{Z} = \frac{E\angle 0^\circ}{R + jX_L}$$

$$I = \frac{E}{|Z|}\angle{-\theta}$$

The voltage across the resistor is equal to

$$V_R = RI_R = R\frac{E}{|Z|}\angle{-\theta} \qquad (14.4)$$

The voltage across the inductor is equal to

$$V_L = I_L X_L$$

Since $I_L = I_R$

then $V_L = X_L \angle 90^\circ \frac{E}{|Z|} \angle{-\theta}$

$$V_L = X_L \frac{E}{|Z|} \angle 90^\circ - \theta \qquad (14.5)$$

The expressions V_R and V_L can be transferred to a polar diagram such as the one in figure 14-9 giving a diagram for the voltages across the resistor and the inductor.

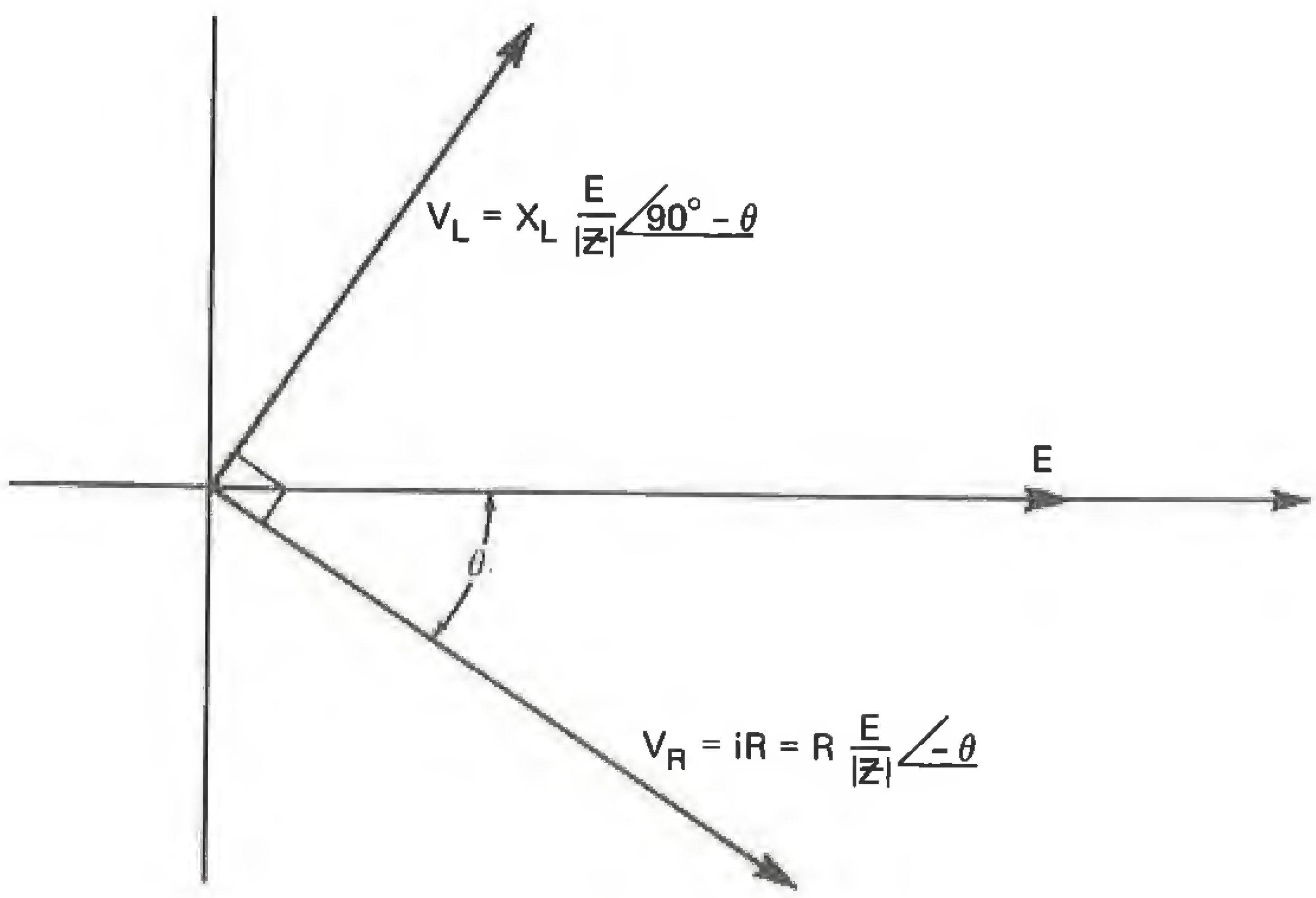


Fig. 14-9 Phasor Diagram Showing Voltages

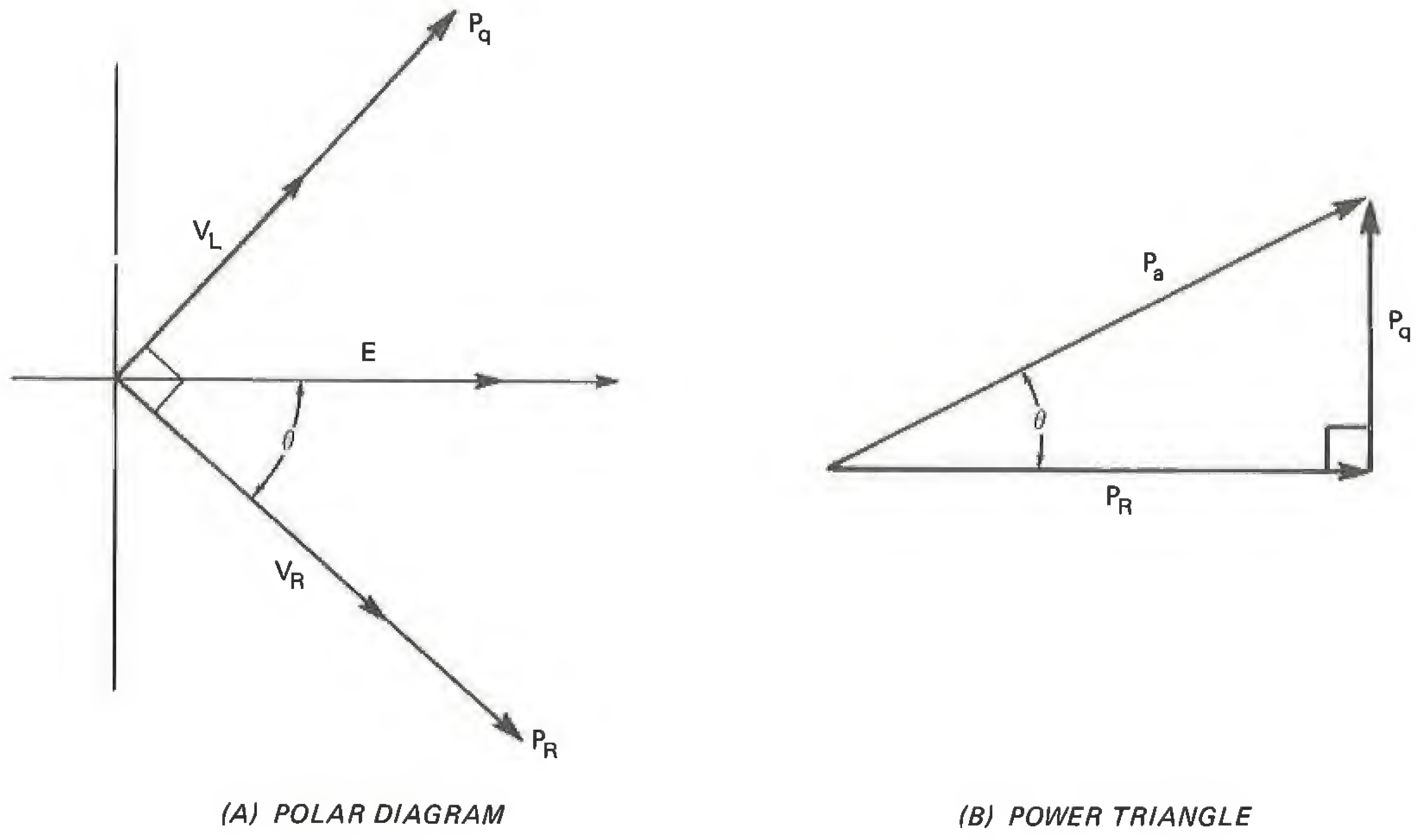


Fig. 14-10 Power Diagrams for RL Circuit

If the current in the circuit was multiplied by each phasor in figure 14-9, an expression for the real power, the apparent power and the *reactive power* could be obtained:

$P_a = EI$	apparent power (volt-amp)
$P_R = I^2R$	real power (watts)
$P_q = IV_L$	reactive power (vars)

The polar diagram and corresponding power triangle is given in figure 14-10.

The *power factor* is defined as the cosine of the angle between the apparent power and the real power.

$$\boxed{pf = \cos\theta = \frac{P_R}{P_a}}$$

In the AC operated relay, the power into the circuit must be greater than the actual power the relay can use. Therefore, the apparent power will be greater than the real power used.

In the DC operated relay where the inductive reactance is zero, the apparent power is equal to

$$P_{a_{DC}} = EI$$

However, the current I is equal to

$$I = \frac{V_R}{R}$$

Therefore, the real power in the circuit is

$$P_{R_{DC}} = I^2R = \frac{V_R^2}{R^2}R = \frac{V_R^2}{R}$$

Since the voltage V_R is equal to the supply voltage E, the apparent power and the real power are equal,

$$P_R = \frac{V_R^2}{R} = V_RI = EI = P_a$$

and the power factor is equal to one.

MATERIALS

5 AC relays, various sizes and shapes

1 Variable Transformer (0-130V 60 Hz)

1 DC power

2 VOM meters

1 AC ammeter

PROCEDURE

1. Connect the circuit as shown in figure 14-11.

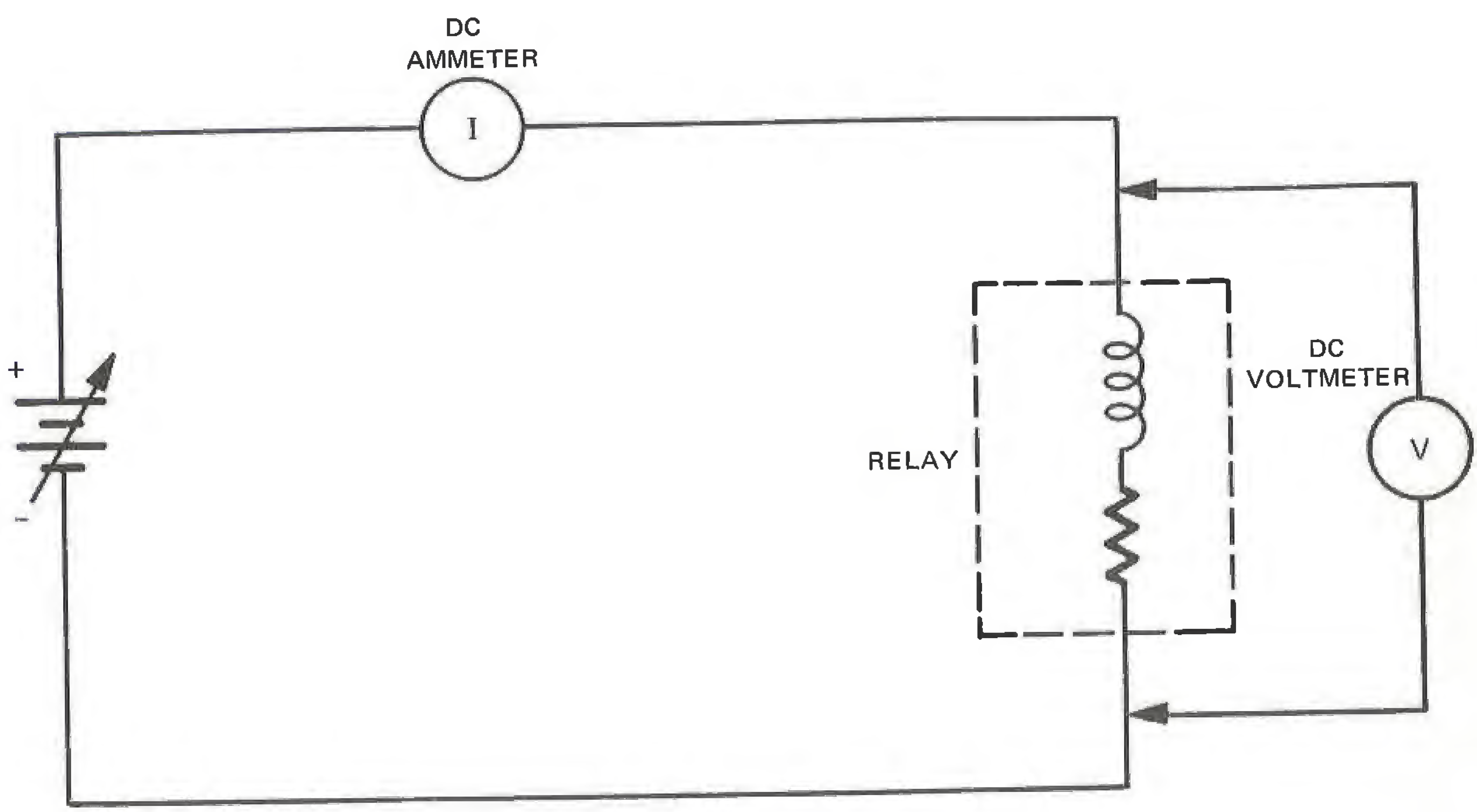


Fig. 14-11 DC Relay Circuit

2. Increase the supply voltage slowly until the relay kicks in.
3. Record in the data table, figure 14-12, the voltage that it takes to operate the relay.
4. Record the current in the circuit when the relay closes.
5. Slowly decrease the supply voltage until the relay releases.
6. Record the voltage and current in the circuit when the relay releases.
7. Run the relay test three times recording the operating and releasing voltage and current each time.
8. Replace the relay with another and rerun the experiment.
9. Run the experiment for all the relays available.

		DC INPUT				AC INPUT			
Relay	Trial	Operating		Releasing		Operating		Releasing	
		Current	Volt	Current	Volt	Current	Volt	Current	Volt
No. 1	No. 1								
	No. 2								
	No. 3								
	Average								
No. 2	No. 1								
	No. 2								
	No. 3								
	Average								
No. 3	No. 1								
	No. 2								
	No. 3								
	Average								
No. 4	No. 1								
	No. 2								
	No. 3								
	Average								
No. 5	No. 1								
	No. 2								
	No. 3								
	Average								

Fig. 14-12 Data Table of Operating and Releasing Characteristics of a Relay

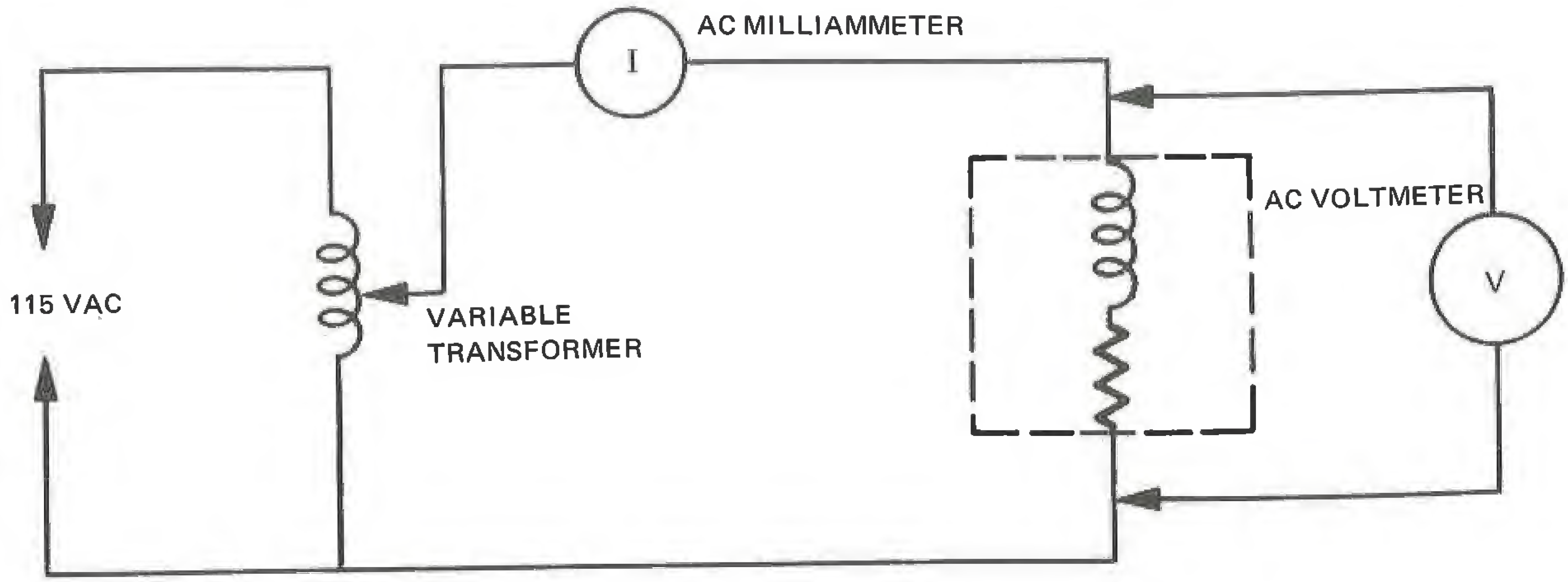


Fig. 14-13 AC Relay Circuit

10. Rearrange the circuit to look like the one in figure 14-13.
11. Increase the AC voltage until the relay closes.
12. Record the voltage and the current that it takes to close the relay.
13. Slowly decrease the supply voltage until the relay opens again.
14. Run this test three times recording the operating and releasing voltage and current each time.
15. Run this part of the experiment for all the relays available.
16. Average the voltage and current for each relay for both the AC and DC input voltages.
17. Calculate the power it takes to close the relays for both the AC and DC input voltages and record the values in figure 14-14 using equation $P = I^2R$.

Operating Power		
Relay	DC	AC
No. 1		
No. 2		
No. 3		
No. 4		
No. 5		

Fig. 14-14 Data Table of Operating Power of Relay

ANALYSIS GUIDE. Make a bar graph using the data obtained of the operating and releasing current and voltage with both AC and DC input for each relay. From the power data, it should be apparent that the power requirements are different when operating under the different inputs.

PROBLEMS

1. Draw a schematic diagram of a circuit with X_L and R in series across a 100-volt source. Calculate Z, i, iR, iX_L and θ for the following values:

a) 100 – ohm R	1 – ohm X_L
b) 1 – ohm R	100 – ohm X_L
c) 50 – ohm R	50 – ohm X_L

2. Calculate the apparent power, real power, and reactive power from the values used in problem one.

experiment 15 RESONANCE VIBRATORS

INTRODUCTION. Vibration in machines not only causes noise, but may cause failure of a vibrating part if its *natural frequency* corresponds to the periodicity of the machine. In this experiment we will examine the phenomena of *resonance* of a vibrating body.

DISCUSSION. Resonance is a condition that exists when effects of the inductive reactance and of the capacitive reactance in an electric circuit are equal. When this condition exists, the total reactance of a series resonant circuit will be zero and its *impedance* will be equal to the resistance of the circuit. In general, the impedance of such a circuit is

$$\boxed{Z^2 = R^2 + (X_L - X_C)^2} \tag{15.1}$$

At resonance the impedance will be at its minimum value.

When a circuit is excited by a DC source, resonance is not available as such. However, if the components are connected like those in figure 15-1, there is a possibility that a condition called *transient ringing* will take place if the value of L and C are in the correct ratio with each other.

The ringing effect is due to the natural frequency of the capacitor and inductor. After a short interval of time (a few micro-seconds), the ringing will be dampened to zero and the current will remain constant.

When an alternating current flows in a circuit, its flow is opposed by the combined effects of resistance and reactance. The current due to inductive reactance lags the voltage by 90°, whereas the current due to capacitive reactance leads the voltage by 90°. Therefore, the effects of inductive reactance and capacitive reactance are 180° out of phase and tend to cancel each other.

If either the capacitor or the inductor in a series resonant circuit is adjusted so that their individual reactances are equal, resonance will occur.

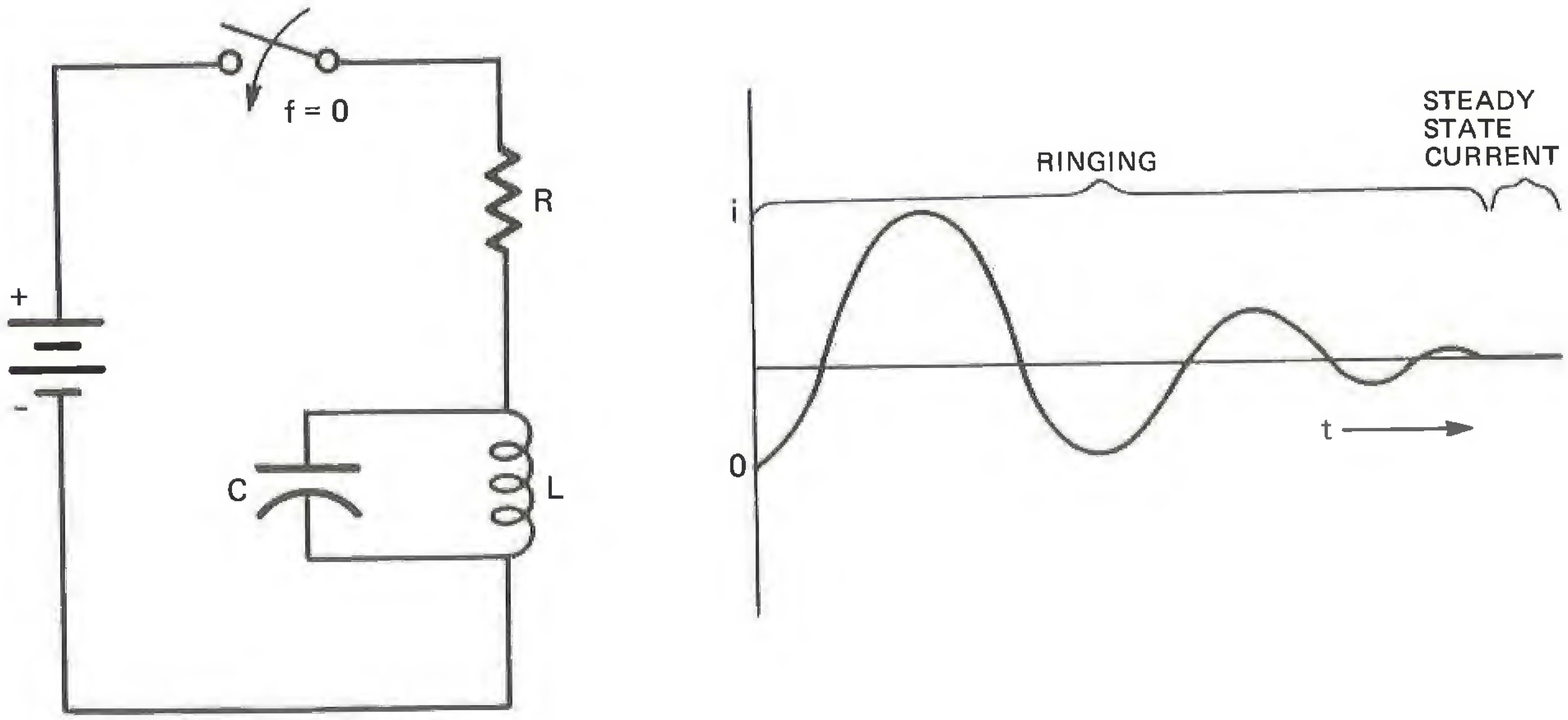


Fig. 15-1 Example of Transient Ringing

From equation 15.1, when $(X_L - X_C) = 0$, the impedance of the resonant circuit becomes equal to

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$
$$= \sqrt{R^2 + 0}$$
$$= \sqrt{R^2}$$
$$= R$$

The current in a series resonant circuit may be expressed as

$$I = \frac{E}{Z} = \frac{E}{R}$$

If the frequency of the supply voltage is changed from the resonant value, the quantity $(X_L - X_C)$ will no longer be equal to zero. Also, if the frequency is kept constant and either the inductance or the capacitance is changed, the quantity $(X_L - X_C)$ will no longer be zero. The reason for these conditions can be better understood by examining the definitions for inductive and capacitive reactance. Inductive reactance is equal to

$$X_L = 2\pi fL \qquad \textbf{(15.2)}$$

where X_L = inductive reactance, ohms
f = frequency of applied voltage, Hertz
L = value of inductance, Henrys

Capacitive reactance is equal to

$$X_C = \frac{1}{2\pi fC} \qquad \textbf{(15.3)}$$

where X_C = capacitive reactance, ohms
f = frequency of applied voltage, Hertz
C = value of capacitance, Henrys

For series resonance, equations 15.2 and 15.3 have to be equal; therefore

$$2\pi f_r L = \frac{1}{2\pi f_r C}$$

where f_r = resonant frequency, Hertz.

Multiplying both sides of the equation by f_r and dividing both sides by $2\pi L$ will give us

$$f_r^2 = \frac{1}{4\pi^2 LC} \qquad \textbf{(15.4)}$$

Taking the square root of both sides we have

$$\boxed{f_r = \frac{1}{2\pi\sqrt{LC}}} \qquad \textbf{(15.5)}$$

This equation is used as a basis for calculating the resonant frequency of *tuned circuits, filters, oscillators,* etc. In some circuits, the inductance may be fixed and the capacitance will need to be found, while in others, the capacitance may be fixed and the amount of inductance must be calculated.

Solving for the inductance in equation 15.4 will give us

$$L = \frac{1}{4\pi^2 f_r^2 C} \qquad \textbf{(15.6)}$$

or, for the capacitance,

$$C = \frac{1}{4\pi^2 f_r^2 L} \qquad \textbf{(15.7)}$$

In many instances, the frequency is expressed in kilohertz, the inductance in microhenrys, and the capacitance in microfarads. When this is done, the more practical forms of equations 15.5, 15.6, and 15.7 will be

$$f_r = \frac{.159}{LC}$$

$$L = \frac{25{,}300}{f_r^2 C}$$

$$C = \frac{25{,}300}{f_r^2 L}$$

where f_r = resonant frequency, kHz
L = inductance, μH
C = capacitance, μF

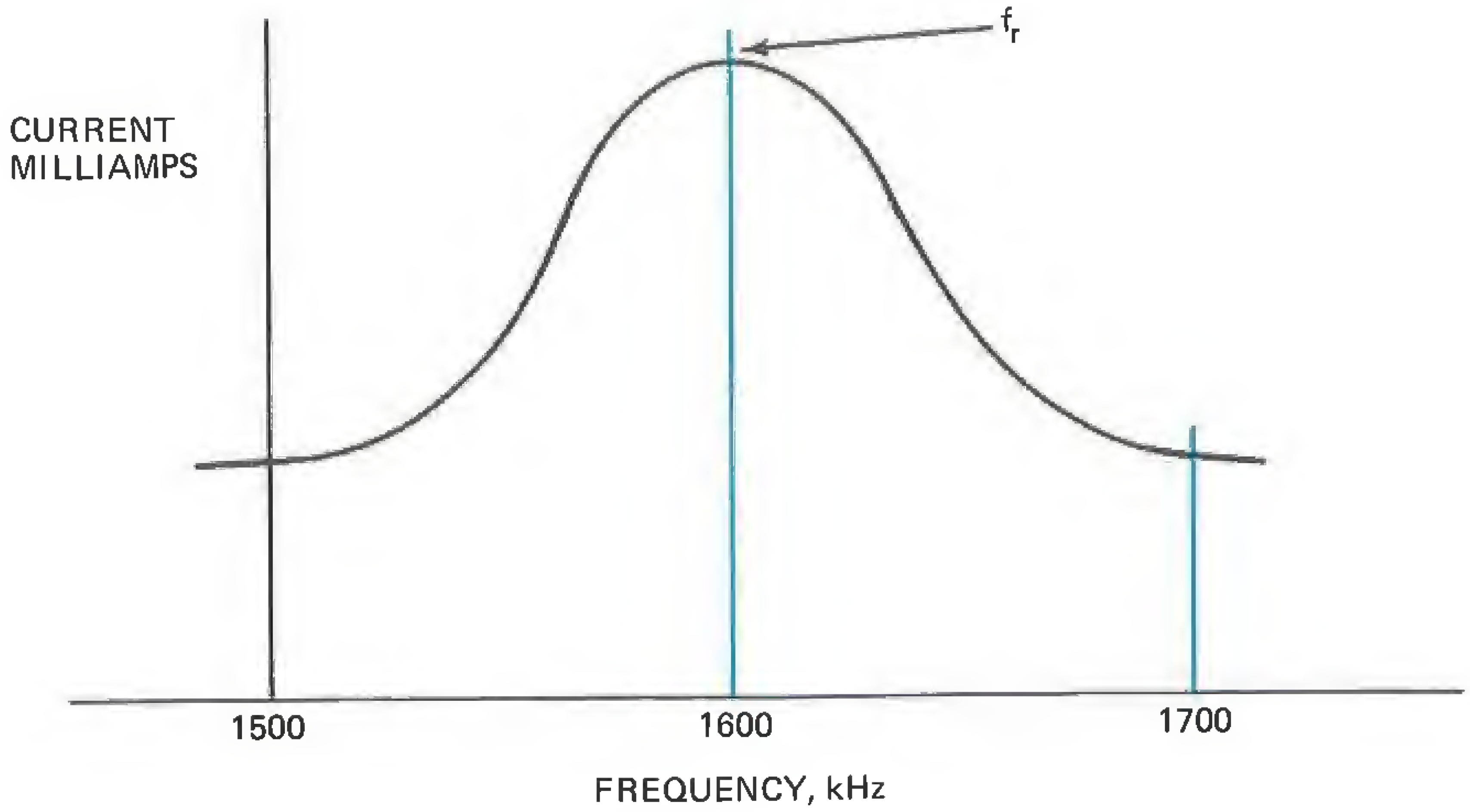


Fig. 15-2 A Series Resonance Curve

If a voltage of constant frequency is applied to a series circuit containing a fixed inductance and a variable capacitance, the capacitor may be adjusted so that the circuit will be resonant at this frequency. If the frequency of the applied voltage is then varied from a value starting below the frequency of resonance and gradually increased to a value above the frequency of resonance, the current flowing through the circuit will vary from a very low value below resonance, increasing until the resonant frequency is reached. At this point the current will be at its maximum value and will decrease to a very low value again when the frequency is increased above resonance. This variation in signal current with frequency change is known as a *resonance curve* and appears as shown in figure 15-2.

A typical curve may be such that no appreciable current flows until the frequency is approximately 1500kHz. The current increases slowly until, at some point close to resonant frequency, it starts increasing very rapidly. At the resonant frequency the current has reached its maximum value. As the frequency is increased above resonance, the current decreases very rapidly at first and then more slowly until no appreciable current flows. A circuit that is or can be adjusted so that it is resonant for a definite frequency is called a *tuned circuit.*

At resonance, the current in a series-tuned circuit (with a constant voltage) is dependent entirely upon the resistance of the circuit. The higher the resistance in the circuit, the lower will be the current at the point of resonance. Therefore, to produce a maximum current, it is best that the resistance of a series-tuned circuit be as low as possible. Figure 15-3 illustrates this point:

Resonance not only exists in electric circuits, but also is apparent when working with solid bodies set in motion by some vibrating wave in the surrounding media.

When a taut string held between two supports is plucked so that a wave is produced, the wave will move along the string until it reaches one end. When it reaches this end it will reflect back toward the other end. It will be inverted if the end is held fixed and it will not be inverted if the end is not fixed. The conditions are shown in figure 15-4.

When two waves on the same string interact as they travel from opposite ends, they may cause *constructive interference* or *destructive interference,* depending on the time at which they pass each other.

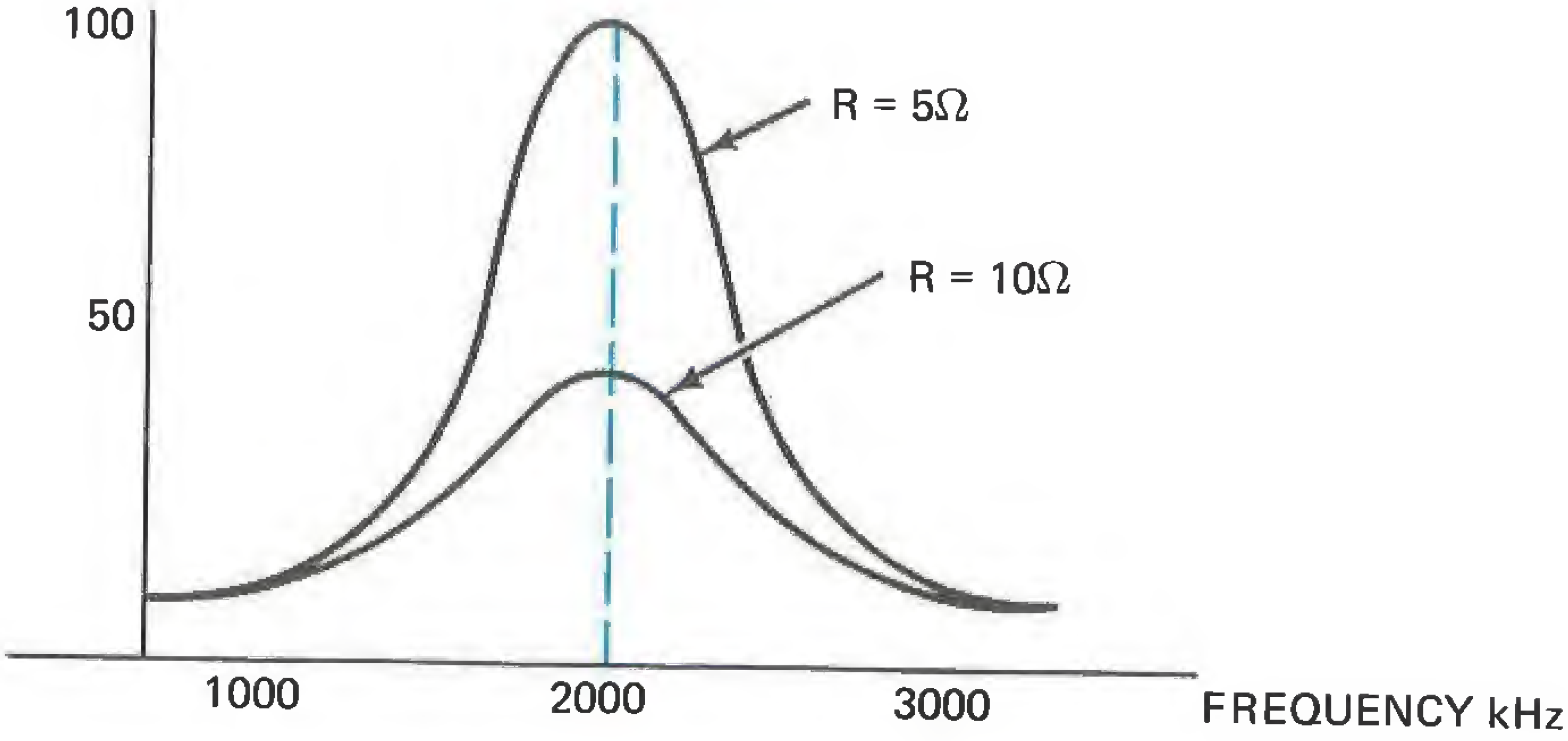


Fig. 15-3 Resonance Curves Showing Effect of Resistance

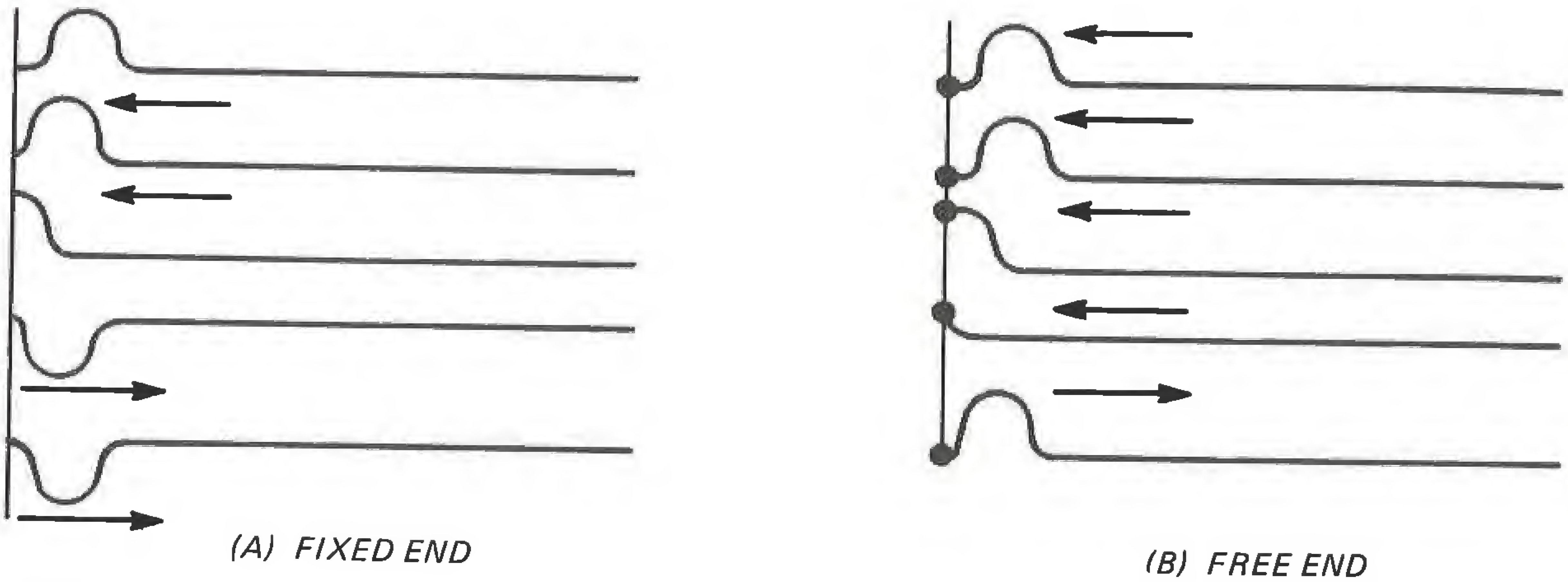


Fig. 15-4 Reflected Waves in a String

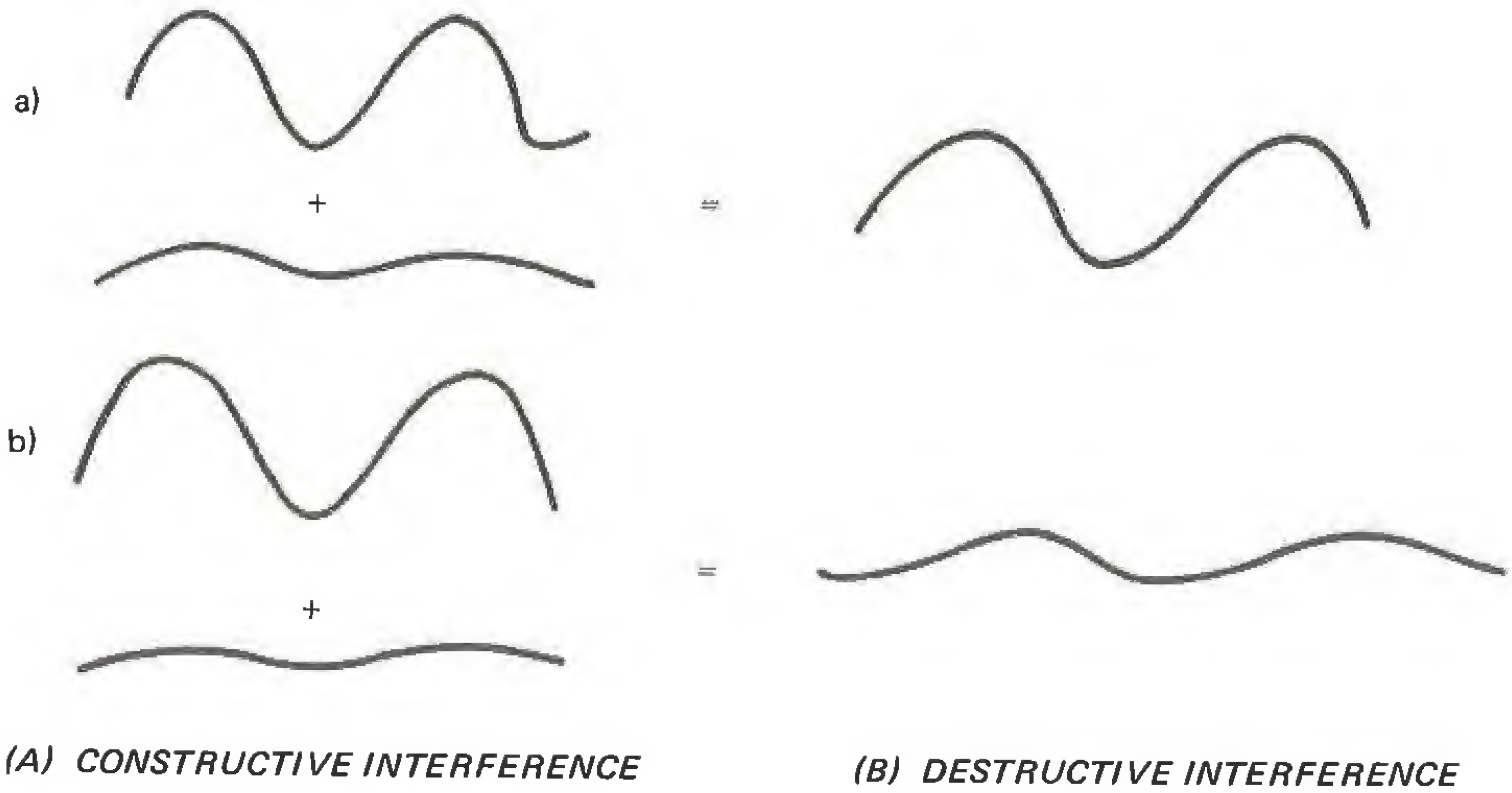


Fig. 15-5 Principle of Superposition

If the two *crests* (high points) simultaneously pass a given point, the height of the resultant wave will be the sum of the two individual waves. If the two *troughs* (low points) simultaneously pass a given point, the height of the resultant wave will fall to a point which is the sum of the two troughs. In the event that a crest belonging to one wave meets a trough belonging to the other, with the amplitude of both the same, there is an exact cancellation.

The principle of *superposition* is a statement of the above behavior and applies to all wave motion. The principle states that when two or more waves of the same nature travel past a given point at the same time, the amplitude at the point is the sum of the instantaneous amplitudes of the individual waves.

When a string is plucked so that waves travel back and forth between its fixed ends, *nodes* are present along the wire where the interfering waves cancel each other. The conditions that exist for nodes to appear at the end of the string restricts the possible wavelengths of standing waves to

$$\lambda = \frac{2L}{n} \qquad n = 1, 2, 3, \ldots$$

where λ = wave length of the wave
L = length of string
n = total number of crests and troughs

This is pointed out in the standing wave of figure 15-6.

The lowest possible frequency of oscillations f_r of a stretched string corresponds to the longest wavelength, λ = 2L. Thus

$$f_1 = \frac{\nu}{\lambda} = \frac{\nu}{2L} \tag{15.8}$$

where ν is the speed of the wave.

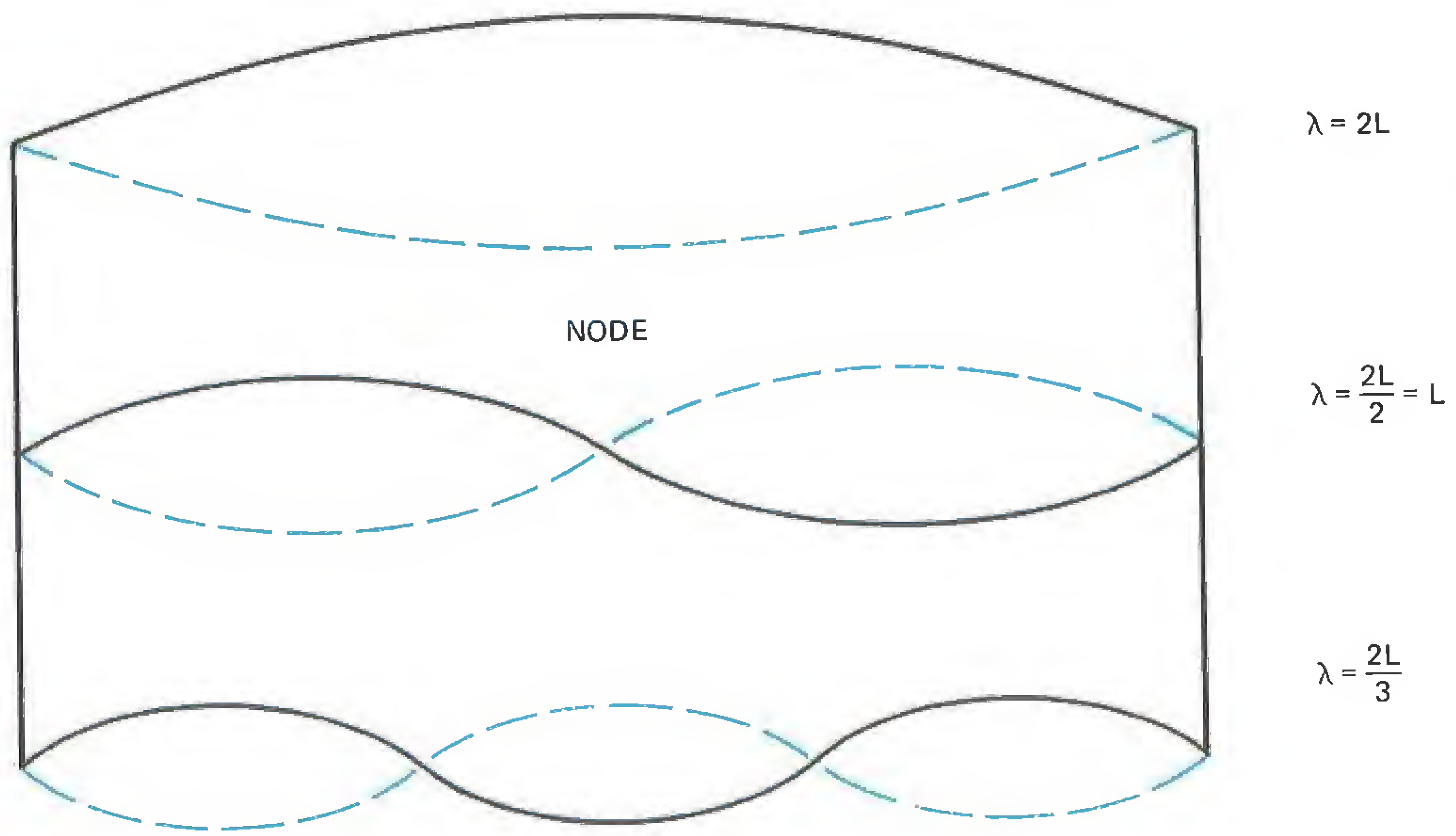


Fig. 15-6 Standing Wave on a String

The frequency f_1 is called the *fundamental frequency* of the string, and the higher frequencies f_2, f_3, and so on, are called *overtones.* Since the wave velocity ν is equal to

$$\nu = \sqrt{\frac{T}{m/L}}$$

where T = tension of the string
m = mass of the string
L = length of the string

equation 15.8 can be expressed as

$$\boxed{f_1 = \frac{1}{2L}\sqrt{\frac{T}{m/L}}} \qquad (15.9)$$

This formula is the basic one used when designing a stringed musical instrument. A short, taut, light string gives a high fundamental frequency whereas a long, less taut, heavy string gives a low fundamental frequency. The tuning of the strings is accomplished by changing the tension of the strings until the desired fundamental frequency is reached.

The internal friction within a vibrating string will cause the vibrations to die out after a short length of time. However, by applying a periodic force to the string whose frequency is exactly the same as that of one of its natural frequencies, the string will continue to vibrate at that frequency. When this is done, the standing waves continue so long as the periodic force supplies energy to the string. If the periodic force exceeds the energy dissipated by internal friction, the amplitude of the standing wave will increase until the string breaks. This phenomenon is called resonance, the same as found in the electric circuit. When periodic impulses are given to the string that are at different frequencies than the fundamental frequency and overtones, little response occurs.

All rigid structures possess characteristic natural frequencies of oscillations even though their vibrations may be more complex than those of a stretched string. These vibrations may be excited by any stimulus of the proper frequency, and depending on how great the force is, damage can result. A good example of this is the shattering of a crystal glass when a violin is played at the correct frequency. Also, a column of soldiers can destroy a bridge by marching across it in step with one another at one of the natural frequencies of the bridge even though the bridge can support the weight of the soldiers when they are not marching.

There are many different methods available for examining resonant vibrations. Among them are electrical and mechanical vibrators which act as *transducers* to change the vibrations to some sort of output which can be observed or measured.

In the electrical method of measuring vibration, an electromechanical pick-up is placed against the machine or the part to be examined and the output is amplified and indicated on a meter, or the waveform may be observed on an oscilloscope.

The transducers used in commercial vibration meters may measure different features of a vibration, such as its amplitude, velocity or acceleration. A very common instrument used to measure vibration is the *piezoelectric transducer.* Other more complicated methods for special applications are also available.

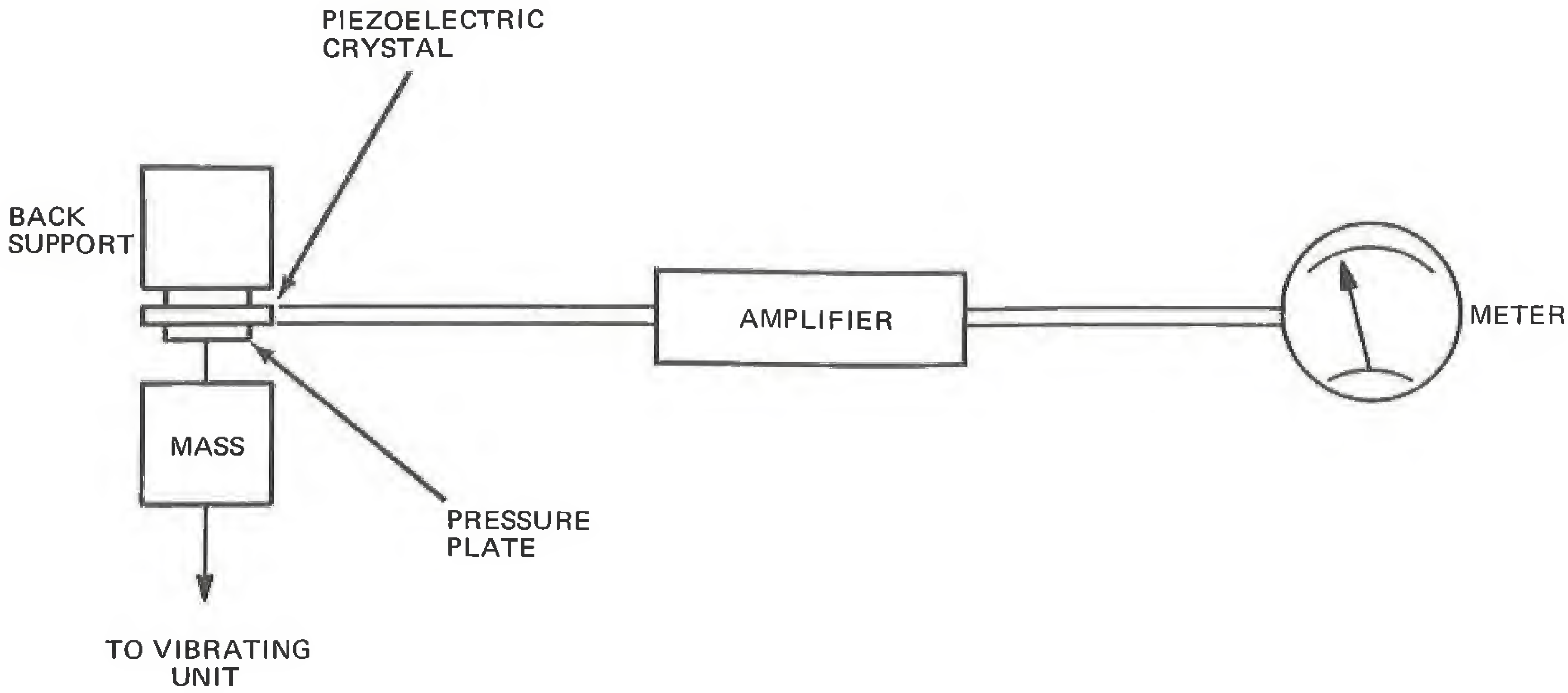


Fig. 15-7 Piezoelectric Method of Vibration Measurement

Piezoelectric transducers may be used by transmitting the force of a mass acted on by a vibration to a piezoelectric crystal as shown in figure 15-7. The crystal will produce a voltage output in proportion to the strain applied to it, and will produce an AC output which has the same frequency as the vibration.

Another type of vibration pick-up is the *electromagnetic* one shown in figure 15-8. The permanent-magnet pole pieces are circular in cross section, so that the coil of fine wire is in a ring-shaped air gap. The vibration to be measured is imparted to the frame of the device and thus to the field structure. The coil is free to move in the air gap and generates a voltage. Mechanically, the motion is analogous to the strain of the crystal in the piezoelectric pick-up. There is, however, one important difference in that the resonant frequency of the coil is low, and the useful range of frequencies lies above the resonant frequency. In this range the coil practically remains fixed in space. Consequently, the relative displacement between the coil and the pole pieces is the same as the displacement of the vibration being tested.

A somewhat different type of frequency meter is the *vibrating-reed instrument.* This meter contains a comb of tuned reeds whose bent tips are visible on the meter face. Each reed is resonant at a different frequency in a closely spaced group. The reed that is resonant at the frequency of vibration will vibrate most vigorously. Frequency accuracy of ± 0.3 percent is obtainable.

Figure 15-9 shows the reed window of a 24 Hertz, reed-type frequency meter. Here, the 24 Hz reed is vibrating while the others are stationary.

Common frequency ranges are 20-27, 27-40, 40-55, 48-52, 58-62, 56-64, 116-124, 380-420 and 390-410 Hz. Commercial instruments have anywhere from 1 to 31 reeds. Some have two or more frequency ranges.

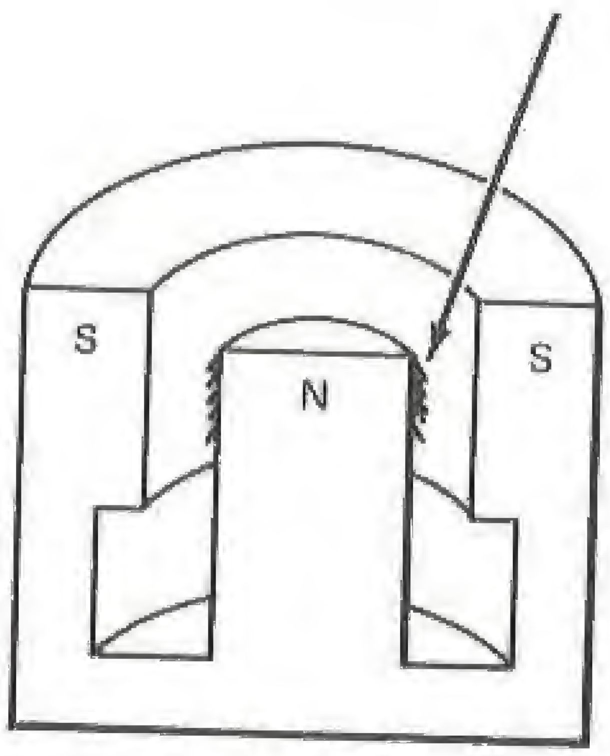


Fig. 15-8 Electromagnetic Vibration Pick-up

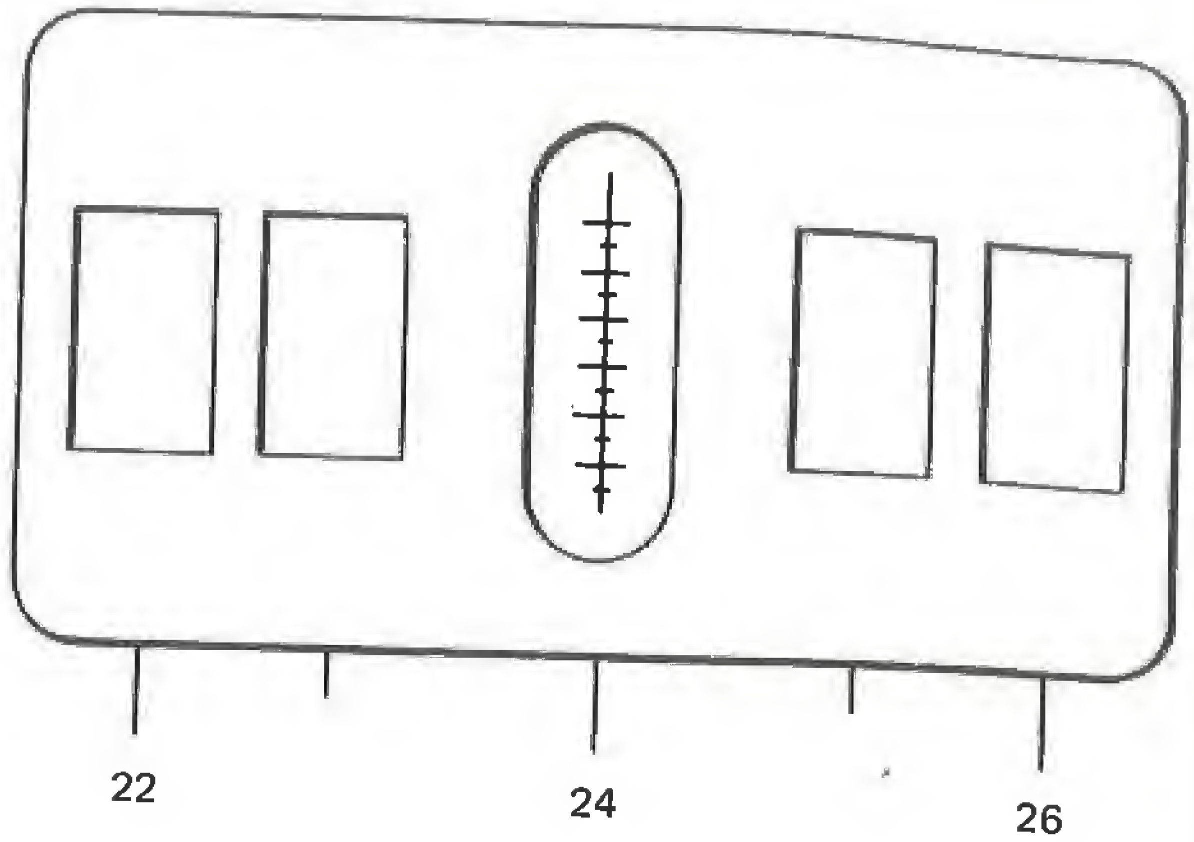


Fig. 15-9 Vibrating-reed Frequency Meter Indicating 24 Hz

MATERIALS

1 DC supply

1 DC motor

1 Motor bracket

5 Small C-clamps

5 Pieces of piano wire, .062 diam.
4-1/2, 5-1/2, 6-1/2, 9-1/2, inches long

1 1000 Ω resistor

1 500 Ω resistor

1 1 μF capacitor

1 1 Henry inductor

1 Audio oscillator

1 VOM

1 Stroboscope

1 Breadboard

1 Collar and large set screw

PROCEDURE

1. Clamp the 4-1/2 inch wires to the set-up as shown in figure 15-10 so that four inches stick out from the clamp.

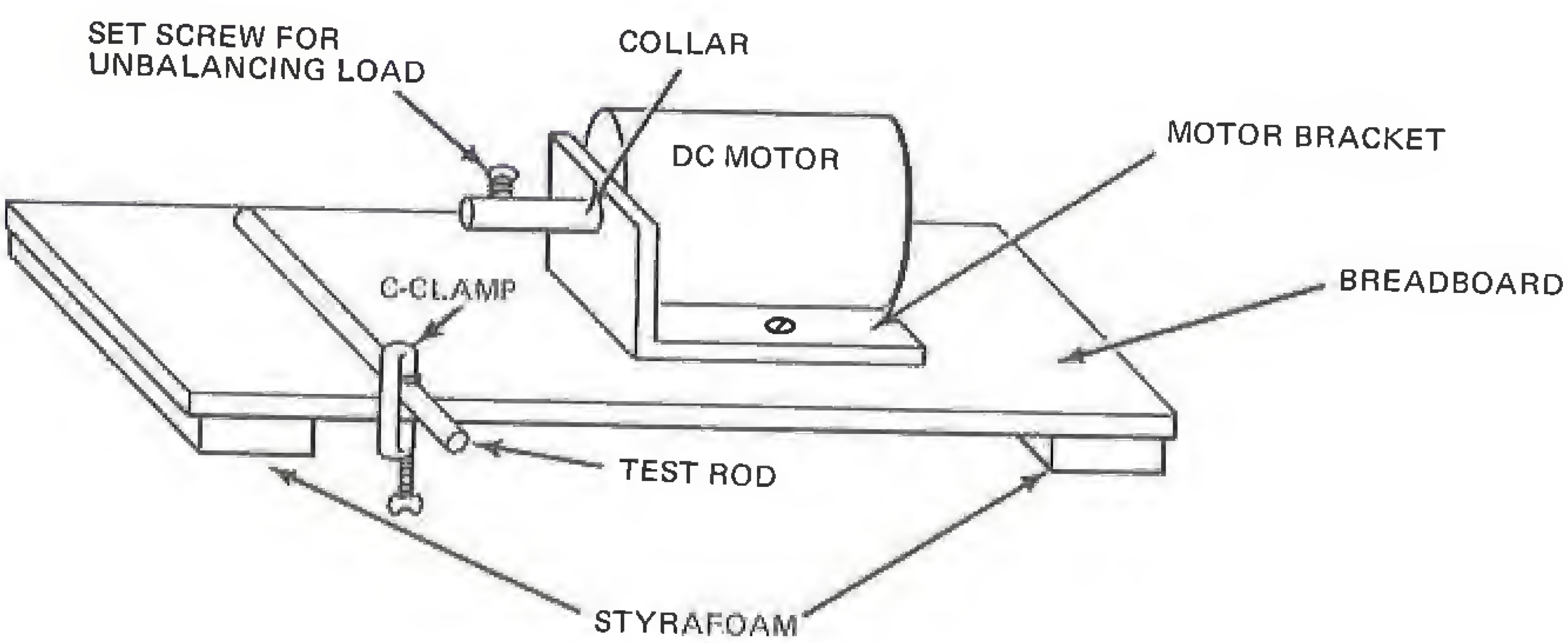


Fig. 15-10 Vibrating Instrument

Wire Length	Speed of Motor, RPM	Frequency of Vibrations
4		
5		
6		
9		

Fig. 15-11 Data Table I

2. Increase the voltage to the motor slowly and notice the end of the wire.
3. When the vibration of the wire reaches its maximum amplitude, strobe the frequency of vibration of the wire. It may be easier to strobe if a small piece of tape is put on the end of the wire. Also strobe the motor speed.
4. It is possible that the motor will drift a little in speed and the frequency of vibration will vary somewhat. However, this should not affect the results obtained.
5. Record the frequency of the vibrations in figure 15-11.
6. Replace the wire with the 5-1/2 inch wire so that five inches stick out from the clamp.
7. Starting at zero, increase the voltage until the wire again vibrates at its natural frequency.
8. Record the frequency of the vibrations and the motor speed.
9. Repeat the experiment for all of the lengths of wire.
10. Clamp all the wires on the breadboard so that they stick out as before.
11. Increase the motor voltage to 25 volts.
12. Turn off the supply voltage and observe the vibrations of the wires.
13. Set up the circuit shown in figure 15-12.

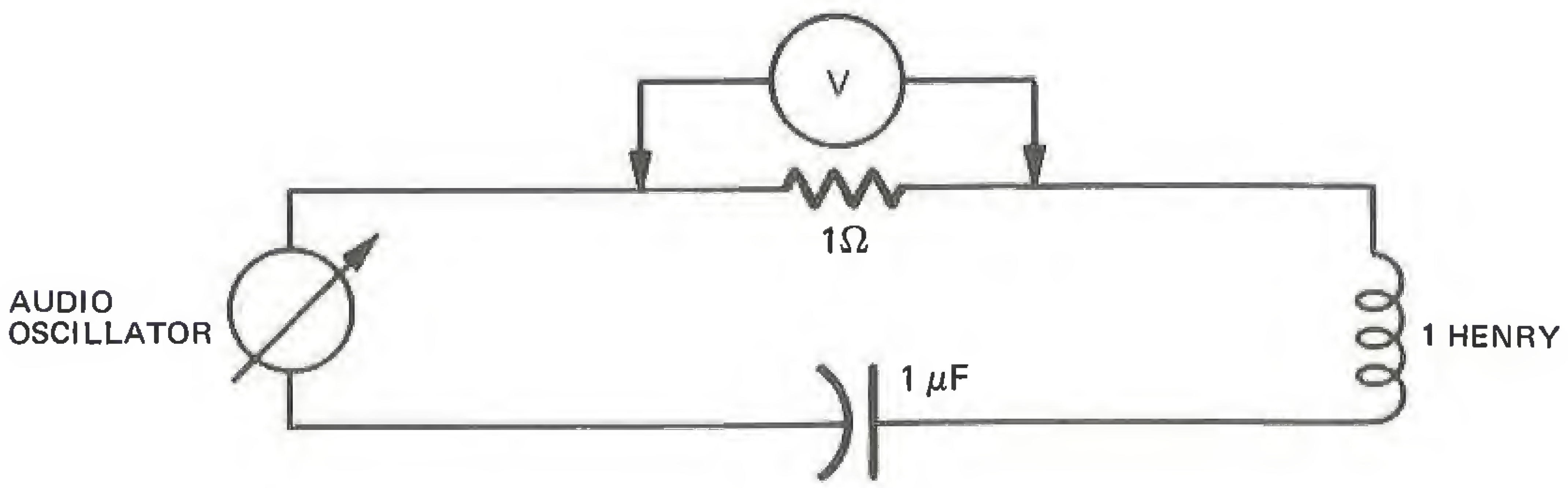


Fig. 15-12 R-L-C Circuit

Frequency	Voltage		Current	
	R =	R =	R =	R =
20				
40				
60				
80				
100				
120				
140				
160				
180				
200				
220				
240				
260				
280				
300				
320				
340				
360				
380				
400				
420				
440				
460				
480				
500				

Fig. 15-13 Data Table II

14. Increase the frequency to 20 Hertz.
15. Record the voltage across the resistor in figure 15-13.
16. Increase the frequency to 40 Hertz.
17. Record the voltage across the resistor.
18. Record the voltage across the resistor for each frequency given in the table.

19. Change the resistor to half that used in steps 13 – 18.
20. Repeat steps 14 – 18.
21. Determine the current in each case for each frequency.
22. Using equation 15.5, determine what the actual resonant frequencies for the circuits should be.

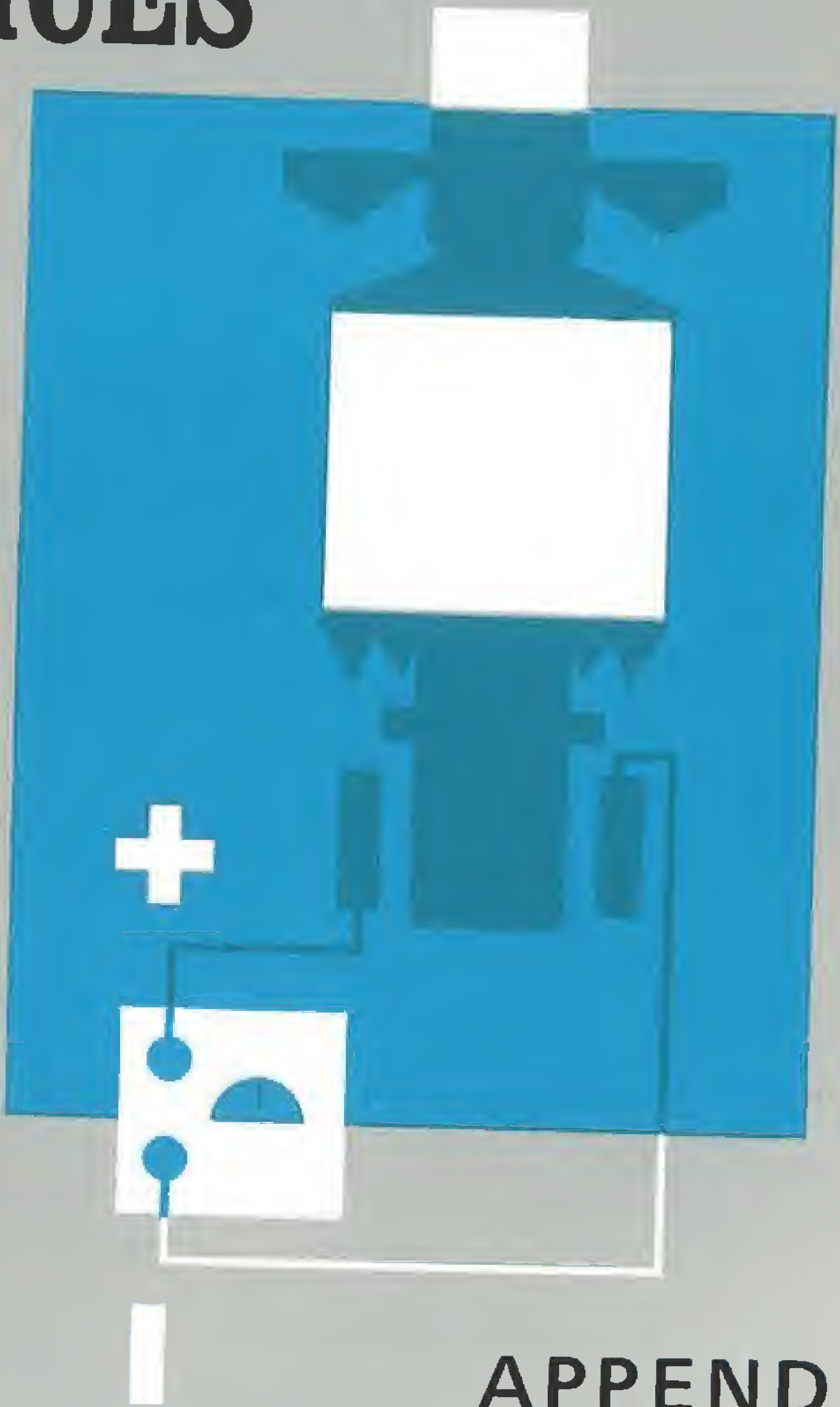
ANALYSIS GUIDE. From the data obtained, plot a graph of frequency of oscillations versus wire length. Also, plot a graph of frequency versus current for both circuits used. These graphs should show characteristics that were covered in the discussion. How far off is the graphed resonant frequency of the electric circuits from that of the calculated frequency?

PROBLEMS

1. What is the frequency at resonance of a series circuit having an inductance of 100 μH if the capacitor is adjusted to 159 μF?
2. How much inductance is required in a series circuit having a capacitance of 250 $\mu\mu$F to produce resonance with a 1000 kHz signal input?
3. To what value must a capacitor in a series circuit be adjusted to produce resonance at 300 kHz if the inductance of the circuit is 400 μH?

ELECTRO MECHANISMS

DEVICES



APPENDIX

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LABORATORY REPORT WRITING

There are a number of different forms that a technical laboratory report may take. The forms proposed here are intended to meet the needs of these experiments and should not be considered to be universally applicable.

I. **THE INFORMAL REPORT.** In reporting the results of these experiments, it may be convenient to write an informal type of laboratory report. Informal reports are normally due at the start of the laboratory period following the period during which the experiment was performed. A report outline which you may wish to follow is given below.

A. **Cover Page.** The cover page should include:
   1. Your name.
   2. Your partner's name.
   3. Date the experiment was performed.
   4. Experiment title and number.

B. **Data Section.** The data section should include:
   1. A neat drawing of the experiment setup.
   2. A list of equipment used, including the manufacturer's name, model number, and serial number.
   3. Measured and calculated data in tabular form.
   4. Curves.

C. **Analysis Section.** The analysis section should contain a satisfactory technical discussion of the data. It should, in general, include brief discussions of each of the points mentioned in the "Analysis Guide" and the solutions to any problems given at the end of the experiment.

II. **THE FORMAL REPORT.** You may be required to write and submit a formal laboratory report on some of the experiments that you have performed. All formal reports should be submitted in a satisfactory report folder, and are normally due about 1 week after the time that the experiment was performed. The formal report should include the following:

A. **Title Page.** The title page should contain the following:
   1. Title of the experiment.
   2. Name of the person making the report.
   3. Date the experiment was performed.

B. **Introduction Section.** The introduction should consist of a paragraph which sets forth the technical objective of the experiment.

C. **Theory Section.** The theory section should include a brief discussion of the theory which is pertinent to the particular experiment.

D. **Method of Investigation Section.** The method of investigation should include the following:
   1. A neat drawing of the experimental setup.
   2. A brief outline of the experimental procedure.
   3. A brief outline of the calculations to be made.
   4. A brief discussion of how the calculations and measurements are to be compared.

E. **Equipment List.** The equipment list should contain every item of equipment used. It should show the manufacturer's name, the model number, and the serial number of every item.

F. **Data Section.** The data section should include a smooth copy of the following:
   1. All measured values in tabular form.
   2. All computed values in tabular form.
   3. All curves.

G. **Sample Computations Section.** This section should include a smooth sample of each type of calculation made.

H. **Analysis Section.** The analysis section should include a discussion of each of the following points:
   1. How valid is the data?
   2. What are the probable sources of error?
   3. What are the probable magnitudes of the different errors?
   4. How could the errors be reduced?

I. **Rough Data Section.** This section is provided to contain all work not presented elsewhere in the report. It should contain such items as:
   1. Notes taken from reference material.
   2. The actual calculations performed.
   3. The actual rough experimental data.

As you have no doubt already concluded, the writing of a formal laboratory report is by no means quick or easy. You should remember however that a technician is frequently judged on the quality of his reports. Therefore, it is wise to make each report as good as possible.

EXPERIMENT 1 ______________ Name ______________

Date: ______________ Class ______________ Instructor ______________

EXPERIMENT 2 ______________ Name ______________________________

Date: ______________________ Class __________ Instructor ______________

Configuration	1	2	3	4	5
Distance in Centimeters					

Fig. 2-15 The Data Table

EXPERIMENT 3

Date: ______________________ Name ______________________

Class ______________ Instructor ______________

TIME	REVOLUTION PER MINUTE (RPM)			
15 sec.				
30 sec.				
45 sec				
1 min.				
Average RPM				
Volts	5V	10V	15V	20V

Fig. 3-12 Volts — RPM Data for Mechanical Tachometer

GENERATOR VOLTAGE/RPM					
Motor Voltage	15	10	15	20	25
Generator Output (Volts)					
Motor RPM					

Fig. 3-14 Volt—RPM Data Table for DC Generator Tachometer

Readings	1	2	3	4	5	6	7	8	9	10
Volts										
RPM										

Fig. 3-15 Volts — RPM Data Table for Stroboscope

EXPERIMENT 4

Date: ______________________ Name ______________________

Class __________ Instructor ______________________

RPM	Cemf (volt. output)
0	0
500	
1000	
1500	
2000	
3000	
4000	
5000	
6000	

Fig. 4-11 Cemf of Motor Versus RPM

From	Experiment		Compute	Compute Power Loss
RPM	E_A	I_a	$E_A - \text{Cemf}$	$P = (E_A - \text{Cemf})\, I_a$
0	0	0	0	0
500				
1000				
1500				
2000				
3000				
4000				
5000				
6000				

Fig. 4-12 Power Loss Versus RPM

EXPERIMENT 5

Date: ____________

Name ____________

Class ________ Instructor ____________

Volts	Force	Torque	Speed	Current	$P_{in} = I^2R$	$P_o = \frac{T\omega}{5250}$	P_o in watts	Ef
50								
50								
50								
50								
50								
50								
50								
60								
60								
60								
60								
60								
60								
60								

Fig. 5-10 Characteristics of a DC Motor Data Table

EXPERIMENT 6

Date: ______________________ Name ______________________

Class ____________ Instructor ______________

Freq.	0	10	35	60	600	6000
V_1						
V_2						
Turns Ratio						

Freq.	0	10	35	60	600	6000
V_1						
V_2						
Turns Ratio						

Fig. 6-15 The Data Tables

$R_L = 1000\ \Omega$

V_{in}	P_{in}	V_o	P_{out}	P_{loss}	Eff.	a
25						
50						
75						
95						

$R_L = 500\ \Omega$

V_{in}	P_{in}	V_o	P_{out}	P_{loss}	Eff.	a
25						
50						
75						
95						

$R_L = 250\ \Omega$

V_{in}	P_{in}	V_o	P_{out}	P_{loss}	Eff.	a
25						
50						
75						
95						

Fig. 6-17 The Data Tables

EXPERIMENT 7

Date: ______________________

Name ______________________

Class __________ Instructor ______________

c = 1μF, E = 50 volts

	t	V_c	P_c
0 RC	0 sec		
1 RC			
2 RC			
3 RC			
4 RC			
5 RC			

Fig. 7-7 The Data Table, Part I

c = 1μF, E = 100 volts

	t	V_c	P_c
0 RC			
1 RC			
2 RC			
3 RC			
4 RC			
5 RC			

Fig. 7-7 The Data Table, Part II

c = 2μF, E = 50 volts

	t	V_c	P_c
0 RC			
1 RC			
2 RC			
3 RC			
4 RC			
5 RC			

Fig. 7-7 The Data Table, Part III

c = 2μF, E = 100 volts

	t	V_c	P_c
0 RC			
1 RC			
2 RC			
3 RC			
4 RC			
5 RC			

Fig. 7-7 The Data Table, Part IV

EXPERIMENT 8

Name ______________________

Date: ______________________ Class ______________ Instructor ______________

Spring	Force, f	Current, I	Defl., d	Spring Constant k	Energy Storage SE
3/4 in.	1 oz.				
	2 oz.				
	4 oz.				
	6 oz.				
	8 oz.				
	10 oz.				
1-3/4 in.	1 oz.				
	2 oz.				
	4 oz.				
	6 oz.				
	8 oz.				
	10 oz.				

Data Table 8-5A Relay Opening

Spring	Force	Current
3/4 in.	1 oz.	
	1.5 oz.	
	2.0 oz.	
	2.5 oz.	
	3.0 oz.	

Data Table 8-5B Relay Closure

EXPERIMENT 9

Name ______________________

Date: ______________________

Class ____________ Instructor ______________

S = 1500 RPM

E	e	V/mm	mm/s	t	i	p
X						
X						
X						
X						

S = 2500 RPM

E	e	V/mm	mm/s	t	i	p
X						
X						
X						
X						

S = 3500 RPM

E	e	V/mm	mm/s	t	i	p
X						
X						
X						
X						

Fig. 9-10 The Data Tables

EXPERIMENT 10 ______________ Name ______________________________

Date: __________________________ Class ________ Instructor ______________

EXPERIMENT 11 Name ____________________

Date: ____________________ Class ____________ Instructor ____________

RPM	Voltage
5000	
4000	
3000	
2000	
1000	
0	

Fig. 11-16 Data Table of Output Voltage Versus RPM

EXPERIMENT 12

Name ________________________________

Date: ________________________ Class ____________ Instructor ________________

Time Max. Temp. Was Reached = ______	Max. Tem. = ______
Time (Min.)	Temp. (Degrees)

Fig. 12-7 Data Table

EXPERIMENT 13 Name ______________________

Date: ______________ Class ________ Instructor ______________

Volts	Force	Torque	Speed	Current	Watts	P_{out}	Power Factor	Eff.
50								
50								
50								
50								
50								
50								
50								
50								
50								
50								
50								
50								
60								
60								
60								
60								
60								
60								
60								
60								
60								
60								

Fig. 13-13 Characteristics for AC Operation
Data Table II

Volts	Force	Torque	Speed	Current	Watts	P_{out}	Power Factor	Eff.
50								
50								
50								
50								
50								
50								
50								
50								
50								
50								
50								
50								
60								
60								
60								
60								
60								
60								
60								
60								
60								
60								

Fig. 13-13 Characteristics for AC Operation
Data Table II

EXPERIMENT 14

Name ______________________

Date: ______________________ Class ____________ Instructor ______________________

		DC INPUT				AC INPUT			
Relay	Trial	Operating		Releasing		Operating		Releasing	
		Current	Volt	Current	Volt	Current	Volt	Current	Volt
No. 1	No. 1								
	No. 2								
	No. 3								
	Average								
No. 2	No. 1								
	No. 2								
	No. 3								
	Average								
No. 3	No. 1								
	No. 2								
	No. 3								
	Average								
No. 4	No. 1								
	No. 2								
	No. 3								
	Average								
No. 5	No. 1								
	No. 2								
	No. 3								
	Average								

Fig. 14-12 Data Table of Operating and Releasing Characteristics of a Relay

Volts	Force	Torc
50		
50		
50		
50		
50		
50		
50		
5		

tructor

AC INPUT

Releasing

Current

Volt

Power	
	AC

g. 14-14 *Data Table of Operating Power of Relay*

EXPERIMENT 15

Date: ______________ Name ______________

Class ______________ Instructor ______________

Wire Length	Speed of Motor, RPM	Frequency of Vibrations
4		
5		
6		
9		

Fig. 15-11 Data Table I

Frequency	Voltage		Current	
	R =	R =	R =	R =
20				
40				
60				
80				
100				
120				
140				
160				
180				
200				
220				
240				
260				
280				
300				
320				
340				
360				
380				
400				
420				
440				
460				
480				
500				

Fig. 15-13 Data Table II